

## UNDERGROUND CABLE SYSTEMS

By

G. W. STUBBINGS, B.Sc., F.Inst.P., A.M.I.E.E.

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# HIGH VOLTAGE CABLES

By

**L. EMANUELI**

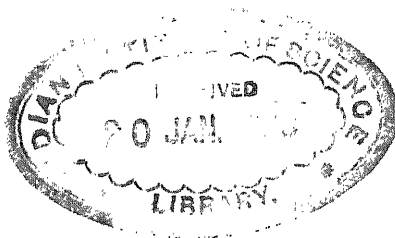
M.I.E.E., M.Amer.E.E.,  
Chief Engineer Società Italiana Pirelli  
and Pirelli-General Cable Works, Ltd.

*WITH AN INTRODUCTION*

By

**Professor C. L. FORTESCUE**

M.A.(Cantab.), M.I.C.E., M.I.E.E.



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# INTRODUCTION

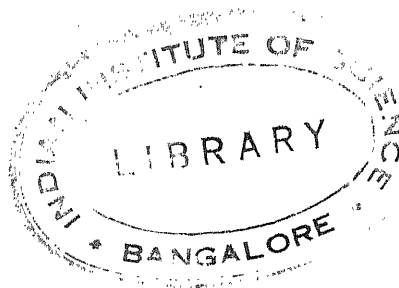
By Professor C. L. FORTESCUE, M.A.(Cantab.),  
M.Inst.C.E., M.I.E.E.

THE history of engineering shows in most branches a more or less clearly defined stage when further advance is only possible by abandoning empiricism in favour of scientific methods based on accurate measurement: both in design and manufacture. Many examples could be quoted, and amongst them that of the electric cable. Only a short time ago a cable operating at 10,000 volts and carrying 5,000 kilovoltamperes was regarded as a triumph of the cable-maker's art. But to-day the demand is for cables carrying 100,000 kilovoltamperes—or even more—at voltages of over 200,000; and this demand is in process of being met satisfactorily. Such development is not the result of haphazard, hit-and-miss methods, but of critical theoretical investigation, exact measurement, and a full understanding of the practical working conditions.

The Engineering Faculty of the University of London were fortunate in being able to arrange for Mr. Emanuelli to give the course of lectures from which this book originated. It touches upon all aspects of the recent developments; the improvement of the design by the use of experimental methods of solving the differential equations of the electric field; the investigation of the physical properties of the materials before their incorporation into the cable; the ingenious devices for building up the cable; and, finally, the electrical and mechanical properties of the completed cable itself. The more modern type of high-voltage cable with which Mr. Emanuelli's name will always be associated is the direct result of these methods. Only by an extensive series of researches, such as those described, could it have been established that the impregnation of the cable was the vital point which had to be improved. It has at last been definitely proved that only a perfectly impregnated dielectric

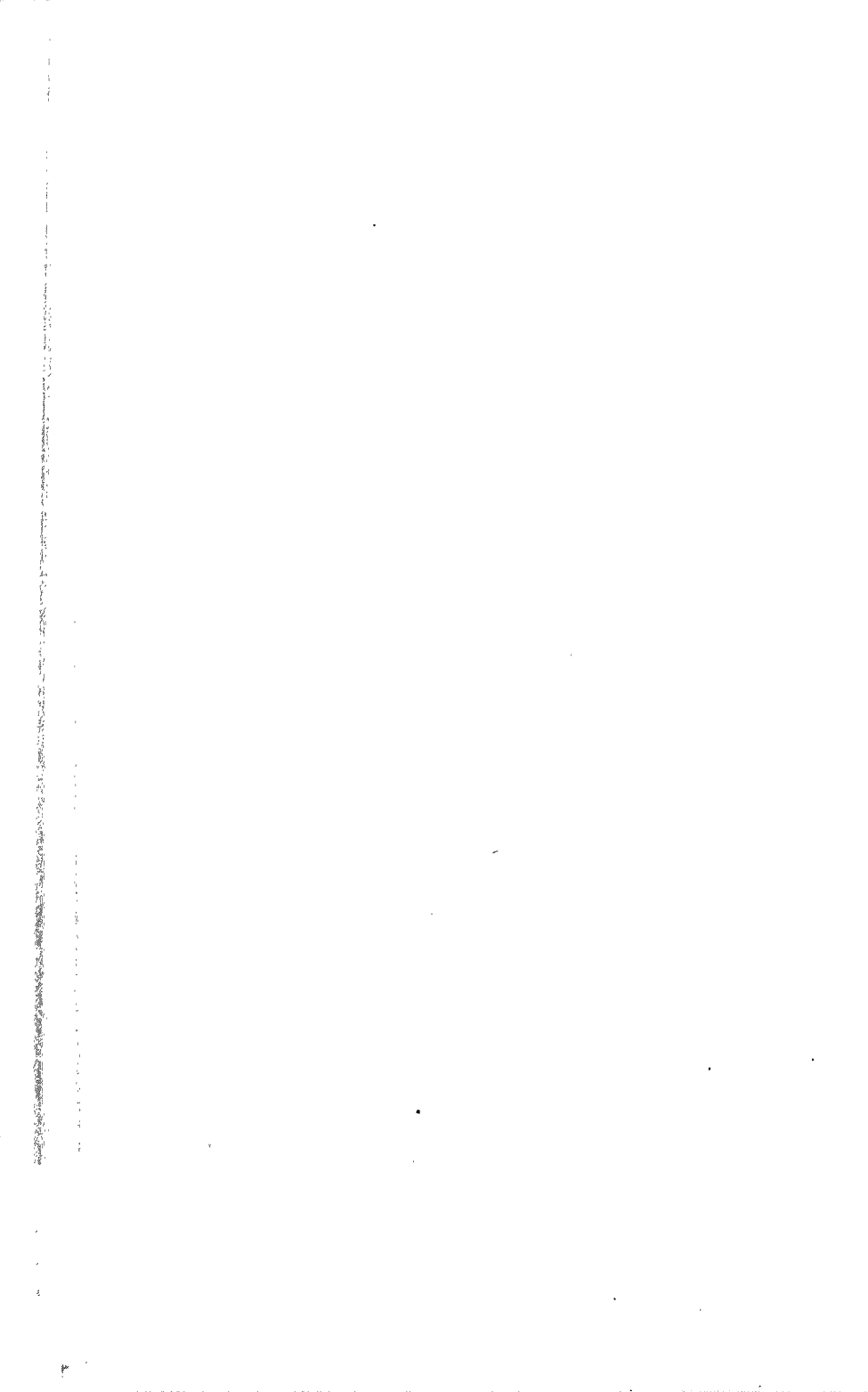
is reliable and that its electrical behaviour can be predicted with exactitude. What more natural, therefore, than that it should be used in cables intended for 100,000 and 200,000 volt lines? This conclusion now is obvious; but it was nevertheless a conclusion that could only be reached after intimate association with all the previous work, just as the method of putting the conclusion into practice was only possible after long experience of the manufacturing methods, of the working conditions, and of the relative costs of the various constituent parts of an electrical power transmission system.

This book should appeal to all engineers, quite irrespective of whether their interests are primarily electrical or otherwise, if only as an example of the effect of the scientific method on engineering production. Few better illustrations of the value of research can be found, and if the book should lead to yet more and more investigation of the properties of insulating materials, this alone will justify its publication.



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## LECTURE I





# HIGH VOLTAGE CABLES

## LECTURE I

### INTRODUCTION

IN preparing the five lectures on high-tension electric cables upon which the book is based, two courses were open : one was to endeavour to say something about all the many points of interest the subject presents ; the other to select one and deal with this thoroughly.

The latter alternative has been adopted and an endeavour has been made to give in detail information which is not readily available in text-books, as it was felt that this would be more useful than a thesis covering a wide range and necessarily very incomplete.

Before starting, however, to discuss the main subject of the lectures, a short outline of general cable construction and types of cable is advisable.

The conductor of a cable is generally made of copper and composed of a number of strands instead of a solid wire, in order to give greater flexibility to the cable. The construction of the conductor is effected by means of a stranding machine, which lays up a number of wires around a single central wire. If a larger conductor is required further layers of wire may be laid up around the first. Each layer is laid up helically around the one preceding it in the opposite direction, and if all the conductors are of equal diameter the number of wires forming a layer is six more than that in the preceding layer.

The insulation of extra high-tension power cables is to-day composed almost exclusively of paper, impregnated with an insulating compound. The paper, which is cut into strips, is lapped round the conductor by means of machines, such as those shown in Fig. 1. The conductor is drawn by a capstan and, at the same time, four or more heads containing rolls

of paper rotate at a constant speed, so that paper tapes are wound helically around the conductor. Fig. 2 illustrates a machine capable of applying a very large number of paper tapes around the conductor simultaneously, in order to build up the considerable thickness of insulation necessary for high-tension cables. The conductor lapped with the required thickness of paper is termed a core, and if a single-core cable is required this core is impregnated with insulating materials. On the other hand, if the cable is to consist of one or more cores, the cores are stranded together helically by machines very similar to the stranding machines.

In Fig. 3, which illustrates one of these machines, the three cores for constructing a three-core cable can be seen wound on the large bobbins, while the smaller bobbins

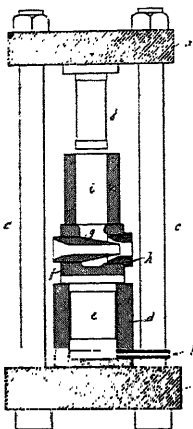


FIG. 4.—Lead Press.

contain what are called fillers. These fillers are made of paper or jute and are stranded together with the cores. As they are purposely of soft material, they are forced quite readily into the spaces comprised between the cores, thus giving the cable a circular formation. The small space left between the cores and the centre of the cable is also filled in the same way.

In an ordinary three-core cable, papers are wound around the three cores, constituting what is known as a belt. It is applied in the same manner as the paper around the cores. In the illustration of the three-core belted type cable shown in Fig. 5, the cores are marked 1, the belt 2, and the fillers 3.

The cable, whether of the single- or multi-core type, is then dried, and for this purpose is placed in a steam-heated tank, hermetically sealed. Vacuum is established and the combined effect of heat and vacuum removes practically all moisture present in the cable.

Impregnating the cable with a suitable compound is the next operation, and is generally effected in the same tank. In order to carry out this operation without breaking the vacuum, a quantity of compound is admitted to the tank

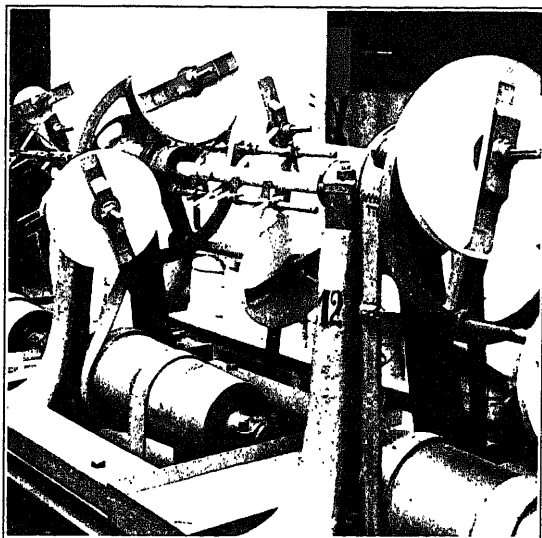


FIG. 1.—Paper Lapping Heads.



FIG. 2.—Paper Lapping Machine.

*To face p. 4.*

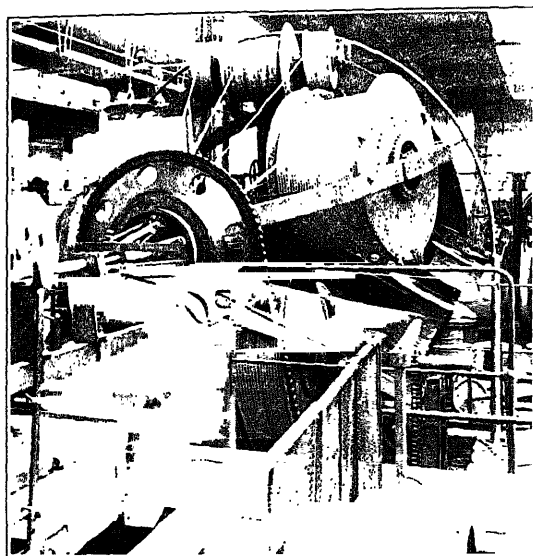


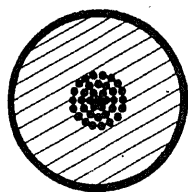
FIG. 3.—Laying-up Machine.

sufficient to fill it completely, or nearly so. After a certain interval the vacuum in the tank is broken and the compound is forced, at atmospheric pressure, through the pores of the paper, thus thoroughly soaking it.

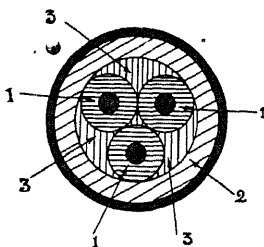
The cable has now to be lead-sheathed. The apparatus used for this purpose is called a lead press, and is shown diagrammatically in Fig. 4.

The cable is passed through a die *g*, kept at a certain determined temperature immediately under the container *i*. *d* is a cylinder into which water under pressure is admitted.

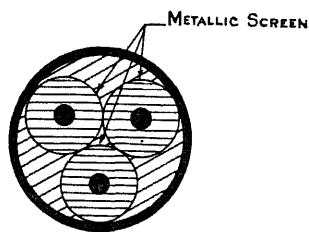
- 1. CORES
- 2. BELT
- 3. FILLERS



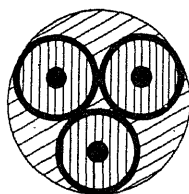
SINGLE CORE



THREE CORE BELTED



H.



T.L.S.

FIG. 5.

The water acting on the piston *e* raises the cylinder *i*, and the plunger *j*, which is stationary, presses the lead around the die *g* and piece *h*, so that the lead is forced to assume the form of a tube when it is extruded through the annular aperture left between *g* and *h*. The cable already impregnated passes through the die *g*, and thus the lead tube is formed around it. The pressure to which the lead must be

submitted to assume the shape of a tube is of the order of 50,000 lbs. per square inch.

If the cable is to be armoured the armouring of steel tapes or wires is applied helically over a bedding of tarred jute or hessian, lapped about the cable by machines very similar to the stranding machines.

The types of super-tension cable now generally in use are the following :—

- Single-core cable,
- Three-core belted cable,
- “ H.” cable,
- “ T.L.S.” cable,

as shown in Fig. 5.

The single-core cable consists of only one conductor insulated with impregnated paper and lead covered. This type is very suitable for high voltages, as the distribution of the electrostatic field is such that there is an absence of stresses acting along the surface of the paper layers and also because the amount of insulation necessary is small when compared with the space occupied by the conductor. A great disadvantage of the single-core cable, however, is that it is not practicable to armour it with magnetic materials, such as steel or iron, as commonly employed for armouring multi-core cables; that is because the electromagnetic field generated by the current flowing through the conductor causes loss of energy in the armouring and also because the presence of the armour when magnetic increases the e.m.f. induced in the lead sheath by the current flowing in the conductor.

The second type shown in Fig. 5 is a three-core belted cable. In this type the three cores, each insulated with a certain thickness of impregnated paper, are stranded together helically, and, as previously mentioned, the spaces between the cores are filled with impregnated paper or jute fillings to give the cable a circular form. Over this, further impregnated paper is wound until the thickness of the insulation between the surface of the conductor and the lead sheath is equal to that between the surface of the conductors. This type of cable has the disadvantage that the distribution of the electrostatic field in the insulation is such that stresses are produced along the surfaces of the paper tapes, and, further, it is a very difficult matter to build up a sufficiently

compact insulation owing to the shape of the assemblage of cores. This type of cable can, however, be armoured and used on a three-phase circuit, because the magnetic flux in the armouring and the currents induced in the lead sheath result in but small losses of energy.

The third type of cable shown in Fig. 5 is composed of three conductors, each insulated with impregnated paper as before, but each core is finally covered with a conductive screen of thin metallic tape or metallised paper. The three cores are stranded together and wormed circular, as in the belted type, but the belt insulation is omitted. The conductive screens of the cores are in contact with each other and with the lead tube, so that the electrostatic field, due to each core, is similar to that of a single-core cable. This type of cable possesses the advantages of a single-core cable, and, therefore, it can be armoured as in the three-core belted type.

The fourth type of cable is composed of three single-core lead-covered cables stranded together. This type is, from the electrical point of view, similar to the last type we have mentioned, and has all its advantages.

The three-core belted type of cable has been extensively used for voltages up to 33,000, although in certain cases they have been used for pressures as high as 50,000 volts. The "T.L.S." and "H." types, however, possess a greater degree of safety, and are now in general use for pressures above 25,000 volts.

For pressures of 66,000 volts and over, the thickness of the insulation required is such that the volume and weight of a three-core cable becomes so great that single-core cables are usually preferred.

## PAPER.

### *General Information.*

For many years manilla paper was used for building up the dielectric of super-tension cables, but the use of wood-pulp paper for this purpose is becoming more and more popular. Manilla paper is made almost entirely from the fibres of old ropes and cordage, which have been disintegrated by boiling with lime. The pulp so obtained is then bleached to a yellowish colour. The fibres are from  $\frac{1}{8}$  to  $\frac{1}{2}$  in. in length and slightly tapered towards the ends, as shown in



Fig. 6, which is a micro-photograph of manilla fibres. Each fibre has a central canal which is rather large and of uniform cross section.

Wood-pulp paper is made from wood from different classes of trees, which is first chipped and then chemically treated so as to dissolve certain constituents in the wood, undesirable in paper on account of their not being so stable as the fibres which, being composed of pure cellulose, offer great chemical stability. The most important of the undesirable properties is lignin, a substance which covers the fibres and causes them to stick together. Two processes are generally used to dissolve lignin or any other undesirable constituent of wood : the soda and sulphite processes. Both processes give a wood-pulp composed almost entirely of pure cellulose fibres. The latter are shorter than manilla fibres, ranging from .1 to .5 in., and they vary in shape according to the wood from which they are derived. The fibres shown in Fig. 7 have been taken from the spruce and have large canals with relatively strong walls.

Besides the fibres, there are often a small number of other cells which have no importance other than that they help to identify the wood from which the paper is made.

After passing through one of the processes referred to above, the pulp is submitted to the beating and refining processes, which have the effect of separating the pulp into loose fibres. These fibres, suspended in water, are carried to the paper-making machine, into which they are deposited to form the paper structure. The operation of pressing and calendering completes the process.

### *Mechanical Properties of Paper.*

For the purpose of cable manufacture no sizing material should be used to increase the strength or to improve the appearance of the paper, nor should a too elaborate bleaching or beating process be adopted, as the durability and electrical characteristics of the paper may be spoiled.

The paper is very carefully tested by the cable maker to ascertain whether any traces of the chemicals used in its manufacture are still present. For this purpose an extract is made with water and the reaction of the extract is tested. The most important chemical properties of cable paper are :

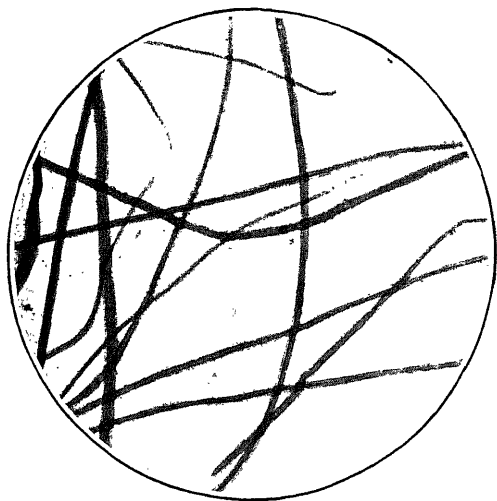


FIG. 6.—Microscopic View of Manilla Fibres.



FIG. 7.—Microscopic View of Cellulose Fibres.

*To face p. 8.*



First, the breaking strength, which is usually expressed in pounds per square inch. As paper is not uniform in texture—the paper-making machines being such that the number of fibres laid in the direction of the length of a roll of paper is greater than that laid transversely—the breaking strength is usually measured on strips, cut both longitudinally and transversely. The breaking strength measured on a strip of paper cut longitudinally is thus greater than that measured on a strip cut transversely. Average values for cable paper are the following :

Longitudinally . . .	7/8,000 lbs. per square inch.
Transversely . . .	3,500 lbs. per square inch.

The second point, perhaps more important from the cable maker's point of view than the breaking strength, is the elongation of the paper under a pull, because the greater the elasticity of the paper the better the mechanical properties of the cable. The elongation corresponding to a pull equal to the breaking force is usually measured, and the following are typical results :

Longitudinally . . .	2 to 2.5 per cent.
Transversely . . .	4 to 5 per cent.

Tearing and bursting tests have also been developed, and a large number of instruments have been devised for this purpose, each one, however, giving figures which are not easily comparable with those of the others.

The resistance to tearing can perhaps be better expressed—using quantities which are universally known—by the product of the breaking strain multiplied by the elongation at a pull equal to that of the breaking point.

The breakdown strength of the paper is effected by its humidity. Tests are usually made in a room in which the humidity is kept constant at 65 per cent., and in which the sample to be tested has remained in the room for a sufficient time for it to reach a constant condition. Paper that has been too much dried becomes brittle. If the paper be carefully dried and then impregnated with the compound used for power cables, the mechanical properties, chiefly the elasticity, change to a considerable extent, as can be deduced

from the following average figures as compared with those given above :

Elongation longitudinally.	. 1.25 per cent.
Transversely . . . . .	. 2 per cent.

Certain vegetable oils have the property, similar to that of water, of improving the mechanical behaviour of the paper, and for this reason have been recommended for paper impregnation—either alone or mixed with mineral oils. Resin added to mineral oil seems to a certain extent to have the same beneficial effect.

Heating in contact with air has a very marked effect on the breakdown strength and elongation of paper. A sample heated at  $110^{\circ}$  C. showed a fall in its breakdown strength of 25 per cent. of its former value in about fifty hours, and of 40 per cent. in the elongation. The same drop occurred in about twenty-five hours at  $135^{\circ}$  C. and in less than ten hours at  $145^{\circ}$  C. This alteration seems chiefly to be due to the oxidation of the paper fibres.

Drying and heating is done in the spaces in the cable under vacuum and no appreciable deterioration occurs. The insulation of a cable is also subjected to heat when the cable is working under a load, but in this condition also it is not subject to contact with the air and the deterioration, at least at the ordinary operating temperatures, appears to be very small.

### *Porosity.*

A very important element of cable paper is its porosity. As a sheet of paper is composed of fibres, which are laid close together but not stuck by means of sizing materials, there is in its texture a large number of canals which are, however, far from uniform in size and length. The more the paper is pressed or calendered the smaller the dimensions of these canals. These canals permit the passage of a fluid through a sheet of paper if a certain difference of pressure is maintained between the two surfaces of the sheet.

The amount of fluid, gaseous or liquid, which passes through a sheet of paper can be considered as proportional to the difference of pressure acting on the two surfaces, provided the flow of liquid is not too great. This is the law

which is generally assumed for the movement of a fluid through a porous medium and for that in capillary tubes.

If we call  $\Delta p$  the difference of pressure acting on the two faces of a sheet of paper,  $S$  its area and  $s$  its thickness, the volume  $V$  of the fluid, having a viscosity  $\eta$ , passing through the sheet in unit time may be expressed by :

$$V = P \frac{\Delta p S}{\eta s}$$

$P$  is a coefficient which depends entirely upon the dimensions of the canals left between the fibres, and may be termed the coefficient of porosity of the paper. This coefficient can easily be determined by measuring the volume of fluid, the difference of pressure, and the other quantities in the expression given above. If all the terms are expressed in absolute units,  $P$ , the coefficient of porosity, will also be in absolute units. The dimensions of porosity are the same as the dimensions of area and can therefore be expressed in square centimetres.

Gases are preferable to liquids in making these tests because when the latter are used the fibres of the paper change their dimensions due to the absorption of the liquids with which they come in contact. Water especially is very unsuitable : kerosene and mineral oil have considerably less effect on the fibres. Air, however, is the best and most convenient fluid to use.

The porosimeter, designed by Dalen, is shown in Fig. 8. In this instrument the amount of air passing through a sheet of paper is measured by means of an ordinary gas meter. On the left of the figure the apparatus shows a sheet of paper fastened between two metal rings, a Woulff bottle, a mercury gauge and the gas meter. A further Woulff bottle enables the pressure to be kept constant. To ensure this a glass tube, shown in the centre of the bottle, provides a communication between the atmosphere and the bottle. A certain amount of water is contained in the bottle, and the glass tube has its lower opening under the water at a depth corresponding to the pressure it is desired to obtain. The other bottle, on the right of the figure, is only for the purpose of providing a certain volume which assists in keeping the pressure constant. The tube which protrudes from the

latter bottle—on the right of the figure—is connected to a water aspirator.

A very simple apparatus (Fig. 9) is formed by an aluminium tube, one end of which can be sealed with a sheet of paper and the other end immersed in water and allowed to float in the manner of a gas reservoir bell. The air contained in the tube is forced by the pressure, caused by the weight of the bell, through the sheet of paper. The time taken for a given length of the bell (the length being indicated by two marks on the bell) to sink into the water is a measurement of the porosity of the paper. This instrument

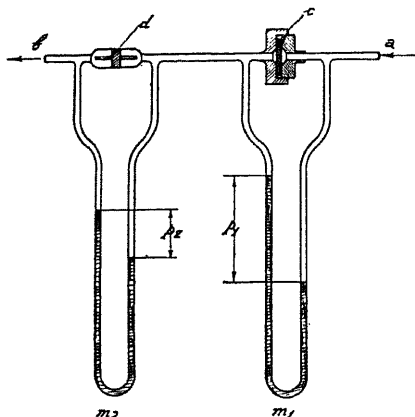


FIG. 10.

is credited to Gurley, and although it has the advantage of great simplicity, it does not give the absolute porosity, but merely a figure which is not easily comparable to those obtained on other instruments of the same type.

A type of instrument due to the author which has the advantage of great simplicity allows tests to be made in a very

short time. This instrument is schematically shown in Fig. 10. In it the sheet of paper, *c*, is compared with a standard of porosity, *d*, which is composed of a capillary tube, this being previously accurately calibrated by measuring the amount of water passed through it in a given time and under a given pressure. The comparison is made by connecting the sheet of paper in series with the standard, and by measuring the difference of pressure on both sides of the sheet and at the two ends of the standard when a gentle current of air is forced through them from *a* to *b*. The ratio of the two pressures,  $p_1$  and  $p_2$ , indicated by the two gauges  $m_1$  and  $m_2$ , multiplied by the value of the resistance to the flow of the standard, gives the resistance of the sheet of paper.

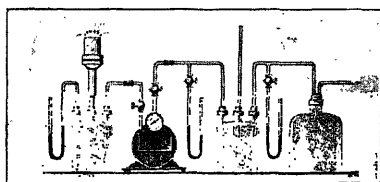


FIG. 8.—Dalen Porosimeter.

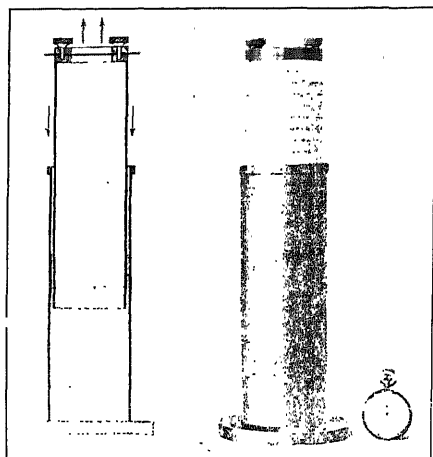


FIG. 9.—Gurley Densimeter.



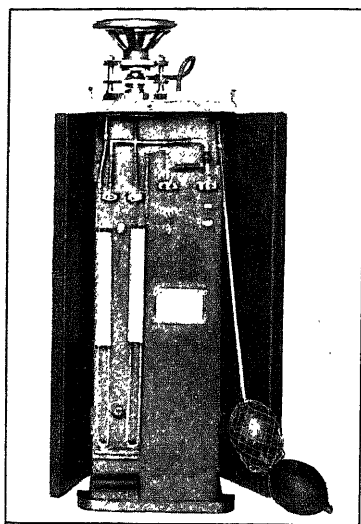


FIG. 11.—Emanuelli Porosimeter.

Knowing this, the area and thickness of the sheet of paper, it is very easy to calculate its porosity. On the top of the instrument shown in Fig. 11 there is a kind of press where the sheet of paper is secured between two metallic cups, one of which communicates with a rubber press-ball which serves to blow a gentle current of air through the paper. The other cup is connected to the capillary tube. The two gauges, one connected across the sheet of paper and the other across the capillary tube, can also be seen in the figure.

One manufacturer employs, instead of the porosity, the impermeability, which may be defined as the reciprocal of the porosity. Let us call  $A$  the impermeability :

$$A = \frac{1}{P}$$

A practical unit,  $10^{-8}$  of the absolute unit, has been used, the absolute unit being too great for practical purposes.

*Porosity of Different Types of Paper.*

	Absolute Porosity.	Imper-meability.
Thin copying paper . . .	$70 \cdot 10^{-12}$	150,000
Filtering paper . . .	3,000 ..	3,000
Cigarette paper . . .	10 ..	1,000,000
Drawing paper . . .	10 ..	1,000,000
Packing paper . . .	20 ..	500,000
Cardboard . . .	15 ..	700,000
Blotting paper . . .	2,000 ..	5,000
Cable paper . . . {	200 ..	50,000
	30 ..	300,000
	5 ..	2,000,000

*Absorption.*

Another interesting characteristic of paper is its ability to absorb liquids. This property, sometimes called absorption, is often ascertained by measuring the height at which a liquid rises on a strip of paper one end of which is dipped

in liquid. A method which is not as empirical as that described above, and which seems to be based on correct assumptions, is that derived from the following considerations :

If on one side of a pile of paper sheets, having a total thickness  $s$ , a liquid is admitted under a pressure greater by  $p$  units than that existing on the other side, the liquid will penetrate the sheets of paper and after a period of time  $t$ , reaches a distance  $x$  from the surface. The time taken to penetrate a thickness  $dx$  is the time required to fill the volume between  $x$  and  $x + dx$ .

If  $S$  is the area of the sheet of paper this volume is  $kSdx$  ;  $k$  is a constant smaller than unity, as the volume  $Sdx$  is not entirely occupied by liquid owing to the presence of the fibres. If  $\eta$  is the viscosity of the liquid,  $P$  the porosity of the paper, and  $dt$  the time taken for the liquid to penetrate a distance  $dx$

$$dt = \frac{\eta x}{PSp} kSdx$$

The time taken by the liquid to flow through a thickness  $s$  is obtained by integrating this equation between the limits  $x = 0$  and  $x = s$ .

Hence :

$$t = \frac{1}{2} \frac{\eta}{P} \frac{ks^2}{p}$$

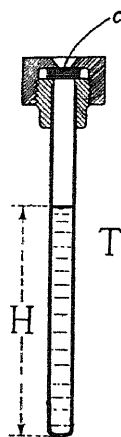


FIG. 12.

The time is therefore proportional to the square of the thickness of the paper and inversely proportional to the porosity and to the pressure which forces the liquid through the paper. This formula can be checked by a very simple instrument, such as that shown in Fig. 12.

In this instrument a glass tube has at one end a metallic device formed so that a pile of paper discs can be pressed together against the end of the tube to form a kind of cell through which the liquid must pass. The other end of the tube has a hole which can be sealed by the finger. This tube is filled to a certain height  $H$  with the liquid to be tested, the hole, of course, being kept sealed by the finger. The paper is then fastened to the other end. By inverting the

tube quickly and leaving the aperture formerly sealed by the finger open, the liquid is forced through the paper by a pressure corresponding to the head  $H$ . It is easy to see when the liquid appears on the other side of the sheet of paper because a black mark becomes visible. The time that has elapsed from the moment of reversing the tube until the appearance of the black mark is recorded and can be compared with the time calculated by means of the formula above.

If several tests are made, using always the same thickness of paper, but a different head of the same liquid, and we plot a curve in which the abscissæ are the pressures, as deter-

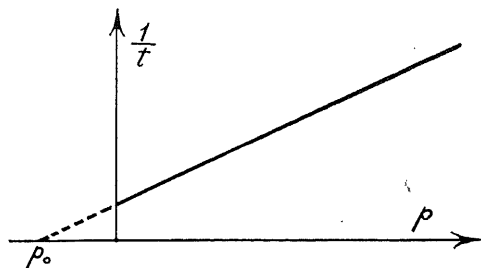


FIG. 13.

mined by the heads  $H$ , and the ordinates the reciprocals of the times taken by the liquid to flow through the paper, a straight line is obtained, which, however, does not pass through the origin of the axis, as would be the case if the above formula took into account the conditions of the tests. The curve which is usually obtained is similar to that shown in Fig. 13. If this is prolonged, as shown by the dotted line in the figure, to cut the abscissæ, a certain negative abscissa is obtained. It is evident that the passage of the liquid through the paper can be considered as being occasioned by a pressure  $P + P_0$ , instead of simply by  $P$ .  $P_0$  is the pressure acting on the sheet of paper when the head of liquid is zero and is due to the force of attraction between the paper and liquid under test. The absorption of the paper may be represented by this pressure. The absorption of different liquids for a given quality of paper, as measured by the above-described method, is given in the following

table, expressed as the head of liquid corresponding to the pressure  $P_0$  in cm.

*Absorption of Certain Liquids by a Given Paper.*

Water . . . . .	10
Alcohol . . . . .	27
Kerosene . . . . .	57
Sulphuric ether . . . . .	16.5
Petroleum ether . . . . .	18.2
Resin oil. . . . .	23

*The Humidity in Paper and the Drying Process.*

Paper absorbs a considerable amount of moisture from the atmosphere, as is shown by Fig. 14. This figure gives

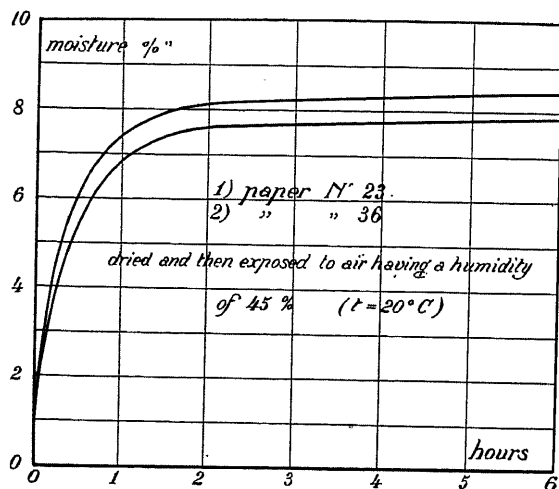


FIG. 14.

the results obtained on two sheets of paper of different qualities first dried and then exposed to air having a humidity of 45 per cent. In two hours a condition of saturation is practically reached corresponding to a humidity of about 8 per cent.

The absorption of moisture has the effect of heating the paper. This can be proved by exposing a thermometer, the bulb of which is wrapped with dry paper, to moist air. It is surprising to note to what extent the temperature rises, 4° or

5° C. being easily obtainable. This rise in temperature is probably due to the fact that the moisture condenses, at least to some extent, on the paper fibres. As is well-known, the mechanical properties of the paper are influenced to a

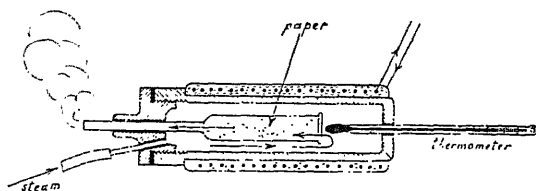


FIG. 15.

considerable degree by the humidity of the surroundings in which the tests are made, and there is no doubt as to the accuracy of the theory that some of the water is also absorbed by the fibres, causing a change in their mechanical properties. It is interesting to note that the amount of water absorbed by the paper from the surroundings is a definite quantity and corresponds to the temperature; the higher the temperature the lower the amount of water contained in the paper. The method of drying can consist only, therefore, in the heating of the paper, but it will be observed that it is not possible to obtain in this way a sufficiently dry paper for electrical purposes.

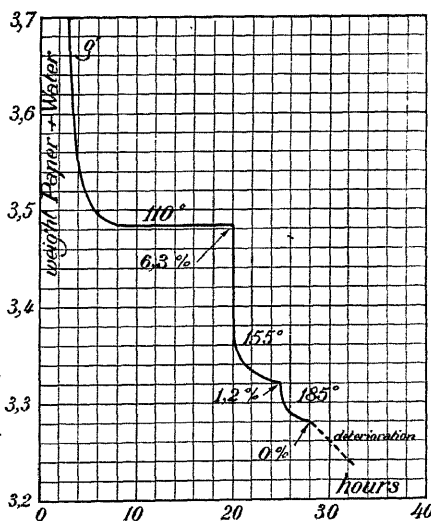


FIG. 16.—Moisture Absorbed by the Paper.

For measuring the amount of moisture absorbed by the paper at various temperatures the apparatus shown in Fig. 15 may be used. The paper, cut into small pieces and placed in a glass tube, is heated in a tubular oven, and a flow

of steam at atmospheric pressure is maintained in order to ensure that the paper is always in contact with the moist vapours. The glass tube can then be weighed and the variation of the water contained therein measured. To eliminate practically all the water contained in the paper and re-establish the weight of the paper when dry a flow of dry air is substituted for the steam.

Fig. 16 illustrates the results obtained on a sample of paper with the apparatus mentioned above. The weight of the paper at different temperatures is plotted as a function

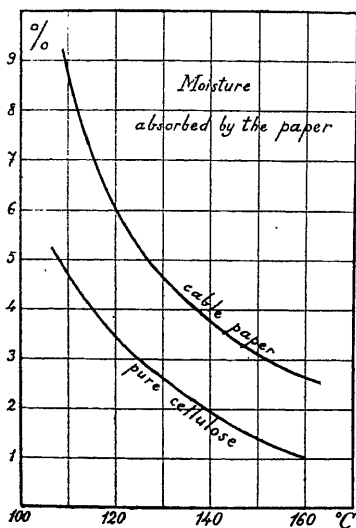


FIG. 17.

of the time of heating at 185° C. It is not possible to reach a constant weight, as it diminishes continuously, showing a distillation of the paper. The temperature of 185° C. has been obtained by other methods, and is said to be the temperature at which paper commences rapid deterioration.

Fig. 17 represents the amount of water obtained with the same instrument as a function of the temperature. Two curves are shown, one for an ordinary good cable paper and the

other for a pure cellulose paper obtained from cotton wool. It is of interest to deduce from these curves what the volume occupied by the steam corresponding to the weight of water absorbed would be. For a cable paper at 120° C. the volume of steam occluded would be forty-three times the volume of the paper; at 150° C. it is about eighteen times the volume. This confirms the theory that the steam condenses on the paper fibres. The curves in Fig. 17 have been obtained at atmospheric pressure, but if the test is repeated at a lower pressure much lower values of the humidity contained in the paper can be obtained. This is illustrated by Fig. 18, which shows the amount of moisture contained in a

cable paper at different temperatures for a pressure of 30 mm. of mercury and also for a pressure of 1 mm. of mercury. From these results it is very evident that in order to remove the humidity from the paper it is necessary to have a high temperature and also a very good vacuum.

The system of drying under vacuum is now generally used by cable makers, and the good results, which are usually obtained in spite of the fact that it is not possible to use as good a vacuum as would appear necessary, probably depend upon the fact that the unavoidable leaks which occur in the drying tanks allow the atmosphere of the tank to be composed of a mixture of moisture and air instead of saturated vapour, and this permits the drying to be partly effected by the diffusion of the moisture contained in the paper into the atmosphere of the tank.

The best method of judging when the drying is complete is to determine the electrical properties of the paper. One method consists in determining the power factor of the dielectric when measured with an alternating current bridge. Another method is that of measuring the insulation resistance and the capacity by the ordinary means. The product of the capacity and the insulation resistance of a condenser depends upon the quality of the dielectric and not upon the shape of the condenser, whatever it may be. This is easily demonstrated as follows :

Let us consider a tube of flux in a condenser of dimensions small enough to allow the corresponding part of two equipotential surfaces at a distance  $dx$  to be considered as forming a plain condenser. The capacity of this elementary condenser is :

$$dc = \frac{\epsilon S}{4\pi dx}$$

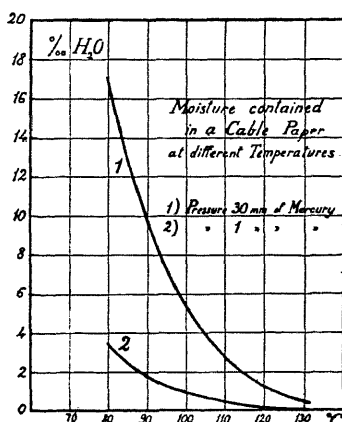


FIG. 18.



where  $\epsilon$  is the inductive capacity of the dielectric, and  $S$  the area.

The resistance is :

$$dR = \frac{\rho dx}{S}$$

that is to say :

$$dc = \frac{\epsilon \rho}{4\pi} \frac{1}{dR}$$

The capacity between the two plates of the condenser, corresponding to the tube of flux considered, can be calculated as follows :

$$\frac{1}{c} = \int \frac{1}{dc} = \frac{4\pi}{\epsilon \rho} \int dr = \frac{4\pi}{\epsilon \rho} r,$$

where  $r$  is the resistance of the tube of flux.

The capacity of the total condenser can be obtained by integrating the capacities corresponding to the single tube of flux, that is :

$$C = \int \frac{\epsilon \rho}{4\pi} \cdot \frac{1}{r}$$

The integral of the reciprocal of the resistance of the elementary tubes is, however, the reciprocal of that of the whole condenser ; we then have :

$$C = \frac{\epsilon \rho}{4\pi} \cdot \frac{1}{R}$$

That is to say :

$$CR = \frac{\epsilon \rho}{4\pi}$$

which depends only upon the properties of the dielectric and not upon the shape of the condenser.

The same thing occurs when the power factor is measured with A.C. Fig. 19 shows the values of the product, insulation resistance by capacity, at different temperatures for a good paper. These values refer to paper which has been perfectly dried and may be used to check whether a condenser formed by a cable has reached its perfectly dry state. It is customary to follow the drying process by measuring either the insulation resistance or the power factor and to consider the process finished when there is no further improvement

in the values measured. This test, of course, can only be made on cables in which it is possible to realise the equivalent of a condenser in which the dielectric is completely

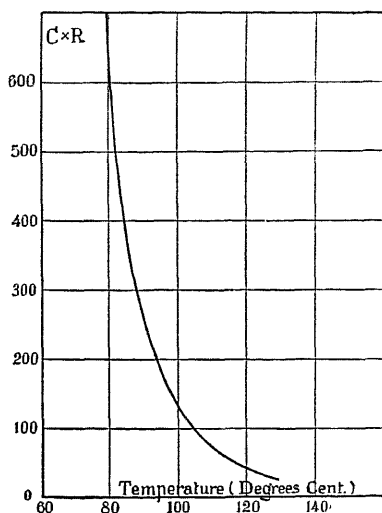
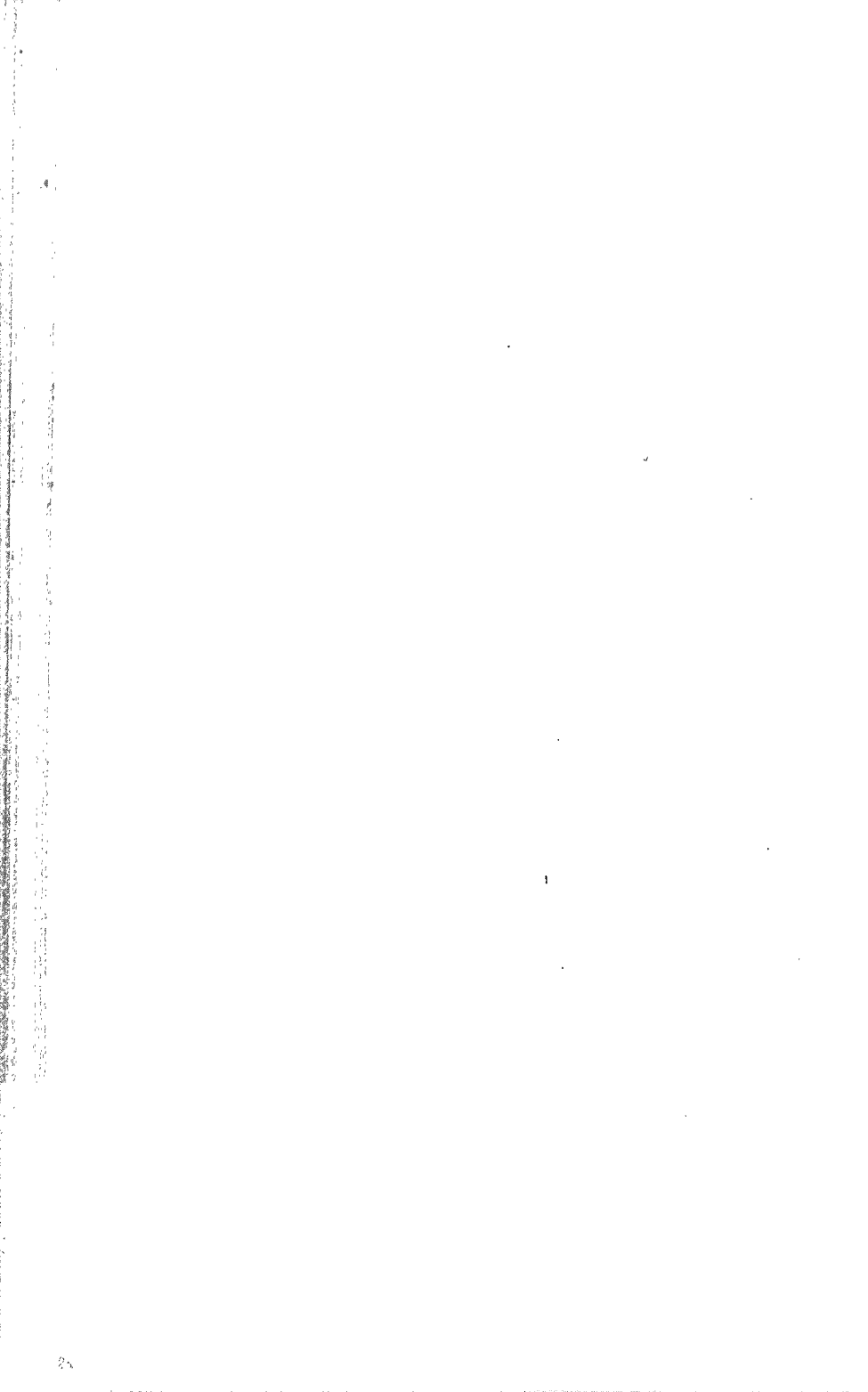
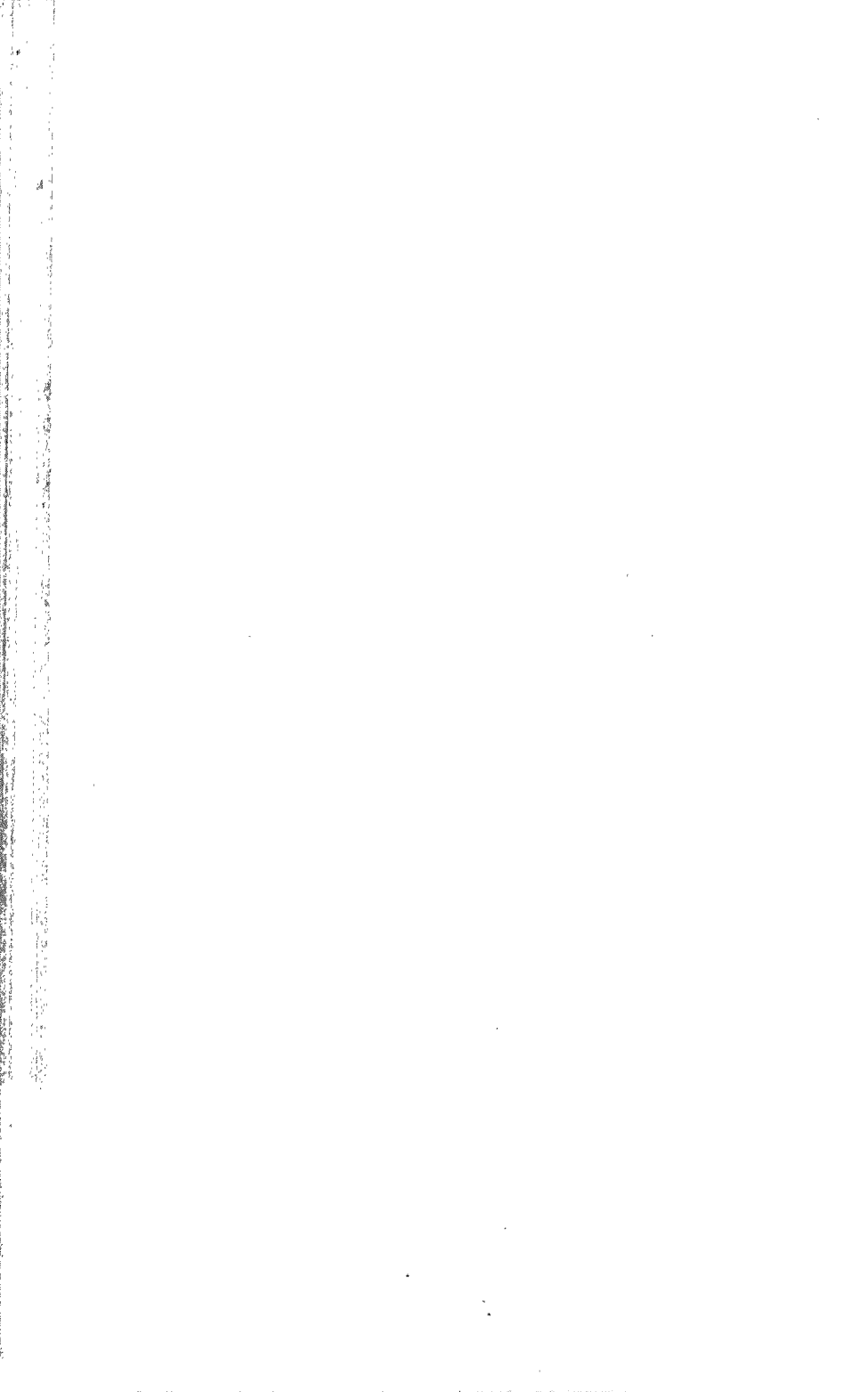


FIG. 19.—Variation of the Product  $CR$  with the Temperature for a Well-dried Paper.

composed of paper, that is on cables having a metallic screen over each core. A three-phase belted type cable can only approximately fulfil these conditions when tested between one core and the other two.



## LECTURE II



## LECTURE II

### IMPREGNATING COMPOUND

#### MINERAL OIL

##### *General Information.*

THE material generally used to impregnate cable paper is mineral oil, to which some manufacturers add a certain amount of resin.

Crude oil is extracted by means of wells sunk in the earth and differs in quality and composition according to the region from which it comes.

Oils which come from Pennsylvania and Virginia belong to the paraffinic series and contain more than 66 per cent. of saturated hydrocarbons of the open chain type.

Oils coming from Texas, Louisiana and California are of the naphthenic series and are more than two-thirds saturated hydrocarbons of the closed chain type. Russian oils are also of this class.

Those oils which are obtained from Ohio, Indiana, Illinois and Rumania are of the naphthenic-paraffinic type and contain terms of either the naphthen or paraffin series in quantities which do not exceed two-thirds of their total value.

The different groups contained in crude oils are separated by fractional distillation. The group which interests the cable manufacturer is that of the heavy oils, paraffin waxes, cylinder oils, etc. These oils are purified by mixing them with sulphuric acid which attacks the constituents of the oil less able to stand oxidation. The oil is then washed with caustic potash and later with water. In order to remove any remaining trace of impurities the oil is finally filtered through Fuller's earth.

##### *Viscosity.*

One of the most important characteristics of an oil and which generally distinguishes it is its viscosity. Viscosity is of great consequence in cable manufacturing because the highly important operation of the impregnation of the cable

is mainly controlled by the viscosity of the compound. Let us consider a surface of a moving liquid in which all the particles have the same velocity, and another surface very near the first in which also the speed is a constant but different from that of the first surface. This difference in velocities sets up a friction tending to equalise the velocities. This friction may be represented by a force  $f$ , which can be expressed by—

$$f = \eta S \frac{v}{s},$$

where  $S$  is the surface area of contact of the two layers of liquid,  $s$  their thickness and  $v$  the difference between the

two velocities;  $\eta$  is a constant which depends only upon the nature of the liquid and is called its viscosity. It may be defined by the formula above and can be expressed in absolute units if  $f$ ,  $S$ ,  $s$  and  $v$  are also expressed in absolute units. The absolute unit of viscosity is called a poise, but as it is too large for practical use, a unit equal to one-hundredth of the poise and called a centipoise is often used. Distilled water at 20° C. has a viscosity of about 1 centipoise.

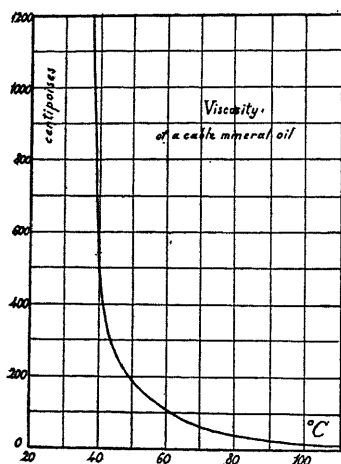


FIG. 21.

Many instruments have been designed for measuring viscosity, practically all being based on the length of time taken for a given quantity of liquid to flow through a tube having a small diameter. One well-known type is that designed by Engler (Fig. 20). In this type of instrument the oil is contained in a small basin, at the bottom of which is the tube through which the oil is to flow. The oil is kept at a constant temperature by placing the basin in an oil bath. Starting from the level marked on the wall of the basin, the time taken for a given quantity of oil to flow into a calibrated flask is then measured. This time is considered a measure of the viscosity.

Other instruments, such as the Saybolt and Redwood types, are based on the same principle. The results given by these instruments, however, are expressed in arbitrary units, but can be converted by means of special tables into absolute units.

Fig. 21 shows the curve of the viscosity as a function of the temperature of an oil used for cable impregnation. The viscosity is expressed in centipoises.

### *Thermal Expansion.*

Another very important characteristic of oil is its thermal expansion coefficient. The experimental method of obtaining this is well-known and does not need further explanation. Fig. 22 shows the expansion coefficient of a cable oil used as a function of the temperature. An average of  $.8 \times 10^{-3}$  per degree Centigrade may be considered as representing the expansion of a cable oil between  $10^\circ \text{C.}$  and  $60^\circ \text{C.}$

The addition of resin does not appreciably change the expansion coefficient, but shellac, on the contrary, produces a great variation, as shown in the figure.

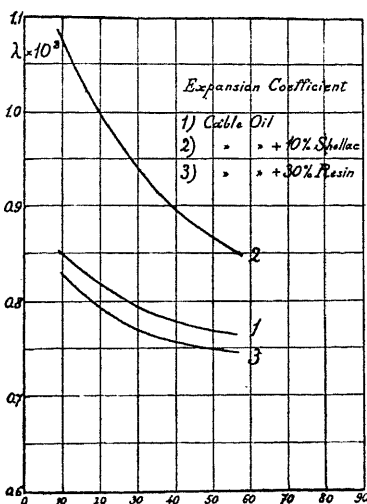


FIG. 22.

### *Gas Absorption.*

Another property of oil which is of importance in cable manufacture is its power to absorb gases. When a gas comes into contact with an oil, a part of the gas dissolves in the oil. The quantity is an amount which depends upon the nature of the oil and of the gas, and also upon the pressure of the gas which comes in contact with the liquid. The quantity of gas dissolved is determined by the Henry Law, which states that :



The quantity of gas, in weight, which can be dissolved at a given temperature in a unit volume of liquid is proportional to the pressure of that part of the gas which remains undissolved. This law can be written as follows :

$$W = kp$$

where  $W$  is the weight of the gas which can be dissolved in a unit volume of oil, and  $p$  is the pressure acting on the oil ;  $k$  is a constant which depends upon the quality of the gas and of the oil, and also upon the temperature. The weight of the gas is, however, a function of its pressure, thus :

$$W = Cvp$$

which means that the weight of the gas is proportional to the product of volume and pressure.  $C$  is a constant depending upon its density.

By substituting in the first formula the value of  $W$  given in the second we obtain :

$$Cv = k.$$

Calling  $a$  the quantity  $\frac{k}{C}$  we have :

$$v = a$$

Thus the volume of gas dissolved is independent of the pressure, its amount being calculated at the pressure  $p$ , and  $a$  is a new constant which is called the solubility coefficient of the gas. This coefficient does not vary very much for the different types of mineral oil used for cables, nor in fluid oils and kerosene, neither does it change much when kept within the limits of temperature which occur during cable manufacture and operation.

The coefficient of solubility for different gases in oils is :

Oxygen . . . . .	0.216
Nitrogen . . . . .	0.126
Hydrogen. . . . .	0.062
Methane . . . . .	0.140
Carbon dioxide . . . . .	1.250
Nitrous oxide . . . . .	2.264
Ethylene . . . . .	0.152

If, in a liquid which already contains a gas in solution, a second gas is allowed to bubble through, this second gas dis-

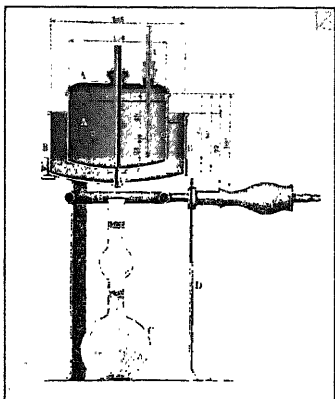


FIG. 20.—Engler Viscometer.

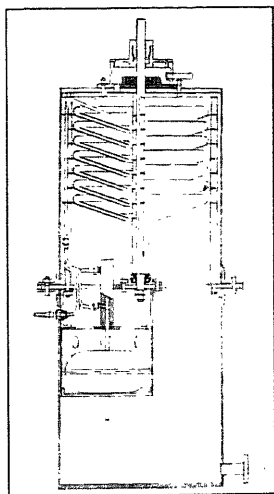


FIG. 23.—Oil Degasifying Machine.



places the first and enters into solution in its place. This is probably the reason why it is sufficient to heat water at boiling point in order to remove gases in solution, as the water vapour which develops in the water displaces the gas in solution.

It is not possible, however, to remove the gases in solution in cable oil by heating unless a very high temperature is reached, which is liable to spoil the oil. A method which may be employed is derived from the Henry Law. The oil is admitted into a tank in which the vacuum is made, and the fact that the pressure acting on it is reduced leads, in accordance with the Henry Law, to a reduction in the weight of gas contained in solution. Consequently a certain quantity of gas emerges from the oil. Unless, however, the oil is well shaken or subdivided into small particles, the entire quantity of gas, which should correspond to this reduction of pressure, does not develop, owing to supersaturation; this is a well-known phenomenon and common to all liquids. The more viscous the oil, the greater the possibility of supersaturation.

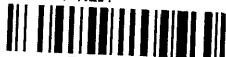
One machine which has been successfully used for the purpose of degasifying the oil is shown in Fig. 23. The oil flows into a tank, in which a good vacuum has been established and is allowed to spray on to a rotating disc. From this first disc the oil is collected by means of a fixed surface, and brought to the centre of a second rotating disc and this sequence is repeated for a number of times. The spreading of the oil along the surfaces and the effect of the rotating discs shakes and divides the oil sufficiently to avoid supersaturation. The degasified oil should, of course, be handled in such a way that it does not come into contact with gas or air at a pressure greater than that at which it has been degasified, so that neither gas nor air can enter into solution.

#### *Electrical Properties — Resistivity.*

The electrical characteristics of oil are, of course, of great importance when studying high-tension cables. The electrical resistivity is very high at low temperature, as can be seen from Fig. 24. With increase of temperature resistivity greatly diminishes. One investigator has put forward the theory that the reduced viscosity of the oil, which allows a

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greater mobility of the ions carrying the current through the oil, is the cause of this decrease in resistivity, but numerical calculations have not sufficiently supported this theory.

The second curve, shown in Fig. 24, refers to the same oil, but in this case the sample has been heated at 130° for seventy-five hours in an open pan. The great reduction in resistivity is accompanied by the formation of oxidation products in the oil which, being acid, seem to be responsible for the fall in resistivity. After the first formation of acid products the formation of polymerisation products follows ;

these products are well-known and give trouble in transformer operation.

The oxidation has a different effect on oils according to their origin and their degree of refinement.

The presence of copper or lead in the oil causes the alteration to occur in a shorter time.

Profiting by the knowledge that the decrease in resistivity

and the formation of acid products are parallel phenomena, the alteration of the oil can be determined either by directly measuring the acidity or by measuring the resistivity.

The oil, after the cable impregnation and lead sheathing, is no longer in contact with the air and there is, therefore, no fear of it losing any of its properties. Before using it, however, the oil should be dried by heating ; it is therefore obvious that it must stand this heating to ensure constant results in the finished cable. If, however, its good properties have been destroyed by the effect of heating in contact with the air, it is possible to regenerate it and obtain an oil which has a high resistivity and low dielectric losses. This can be done by filtering the oil through Fuller's earth or similar

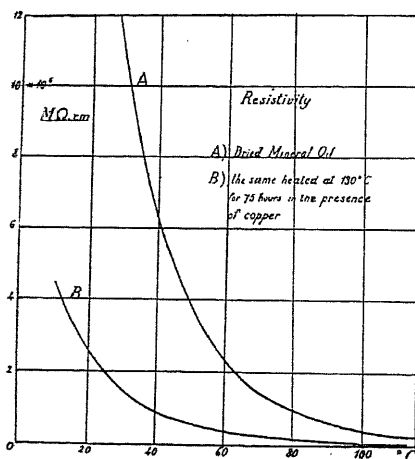


FIG. 24.

ingredients. It appears that Fuller's earth, probably because of its high subdivision, has the property of absorbing the products of oxidation in the oil. Many cable manufacturers use a similar system of regeneration of oil.

### *Dielectric Losses.*

Besides the conductivity of the oil increasing due to heating, there is also an increase in the dielectric losses, and it would not be out of place to recall some fundamental ideas

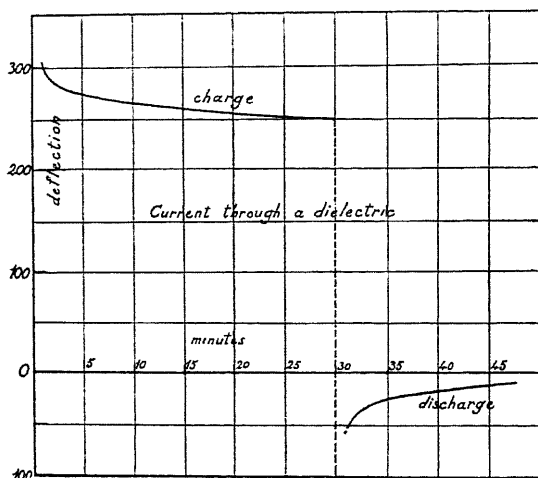


FIG. 25.

regarding dielectric losses, considered as a consequence of dielectric absorption.

As is well-known, the current which flows through solid or liquid dielectrics is not only a function of the applied difference of potential but also of time. Fig. 25 shows the current flowing through the dielectric of a cable as a function of time. The capacity current is not represented here. After a certain time, generally of long duration, the current assumes a constant value, and this can be considered as the true conductivity current through the dielectric. The first part is called the absorption current.

In practice, however, when we mention the resistance of a condenser or the insulation resistance, as it is called, we do not mean the resistance deduced from the true conductivity

current, but that deduced from the current measured after one minute of electrification. Of course, the smaller the absorption the smaller also is the difference between the resistance after one minute and the true resistance of the condenser.

If, after having connected a condenser to a difference of potential for a certain time, we connect it to a galvanometer, we first notice the capacity discharge current and then a current which diminishes with the time, more or less rapidly according to the quality of the dielectric. This is called the residual discharge.

Let us suppose that a condenser, having a perfect dielectric,

such as non-ionised gas, is connected to an alternator giving an electromotive force :

$$e = E \sin \omega t$$

where  $\omega$  is  $2\pi$  times the frequency. The capacity current flowing through the circuit is :

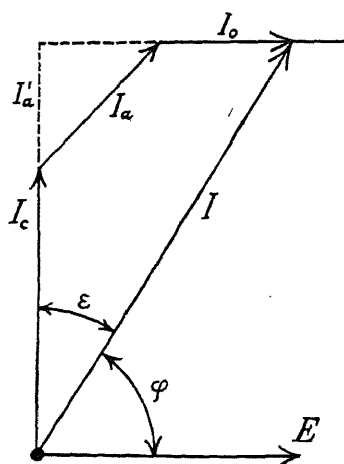
$$i_c = CE \sin \left( \omega t + \frac{\pi}{2} \right)$$

where  $C$  is the capacity of the condenser.

If we substitute a liquid or a solid for the non-ionised gaseous dielectric there is, besides the current capacity

which is due to the geometrical dimensions and to the specific inductive capacity of the dielectric, the absorption current (see Fig. 26).

If  $E$  is the electromotive force and  $I_c$  the capacity current, the absorption current can be represented by  $I_a$ , which follows the capacity current with a certain time lag. We then have the true conductance current  $I_o$ , which is in phase with  $E$ . The total current is  $I$ , which leads the electromotive force by an angle equal to  $\varphi$ . The component of  $I_a$  at  $\frac{\pi}{2}$  with  $E$  is similar to a capacity current which we may



[FIG. 26.]

call  $I'_a$ . This all takes place as the capacity of the condenser is increased from its value  $C$  to the greater value  $C^1$ . As  $I'_a$  varies with the frequency, so does  $C^1$ .

The power dissipated in the condenser is given by

$$W = I_{eff} E_{eff} \cos \varphi$$

But

$$\begin{aligned} I \cos \varphi &= (I_c + I'_a) \tan \epsilon \\ &= (I_c + I'_a) \cot \varphi \end{aligned}$$

and

$$I_c = I'_a = \omega C^1 E$$

We can therefore write :

$$W = \omega C^1 E^2 \cot \varphi.$$

This formula contains  $C^1$ , a part of which characterises the geometrical dimensions and the specific capacity of the

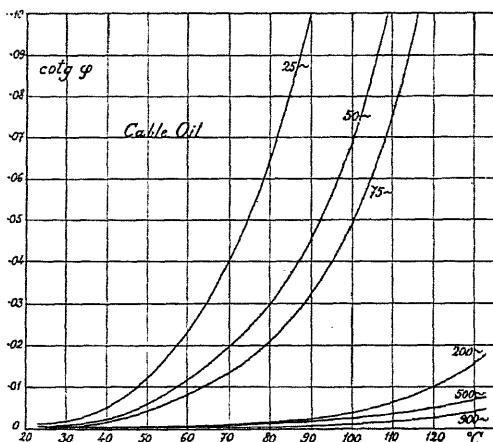


FIG. 27.

dielectric and depends partly upon the absorption of the dielectric. The other component,  $\cot \varphi$  does not depend upon the geometrical dimensions, but only upon the quality of the dielectric and its temperature.

Fig. 27 shows the value of  $\cot \varphi$  for a cable oil as dependent upon the temperature and the frequency of the current used to make the test. The temperatures are plotted as abscissæ and the values of  $\cot \varphi$  for the different frequencies as ordinates.  $\cot \varphi$  increases very much at high temperatures,



which is probably due to the increase in the conductivity of the oil.

As the electric absorption of oil is very small, especially at high temperatures, the conductivity seems to be the principal cause of the dielectric losses, especially at high temperatures.

From the value of  $\cot \varphi$  and the capacity of the condenser it is easy to calculate what is called the apparent resistance. This can be done as follows :

Suppose that the condenser has a perfect dielectric and that a resistance is shunted across it. If its value is such that

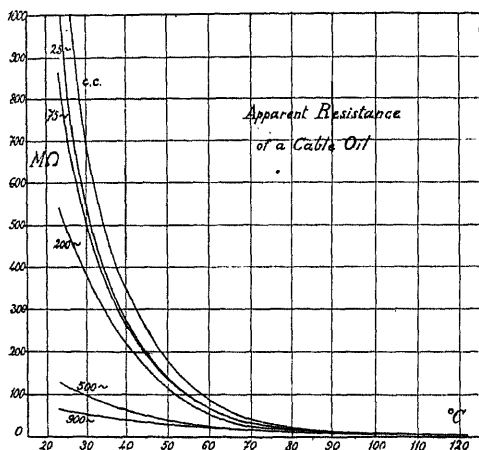


FIG. 28.

the power lost in it is equal to that dissipated in the condenser under test, then this may be called the value of the apparent resistance.

This can be expressed as follows :

$$W = \omega C^2 E^2 \cot \varphi$$

If R is the apparent resistance we have

$$W = \frac{E^2}{R}$$

hence

$$R = \frac{1}{\omega C^2 \cot \varphi}$$

Fig. 28 shows the apparent resistance of the condenser, of which the  $\cot \varphi$  values have already been shown. The value

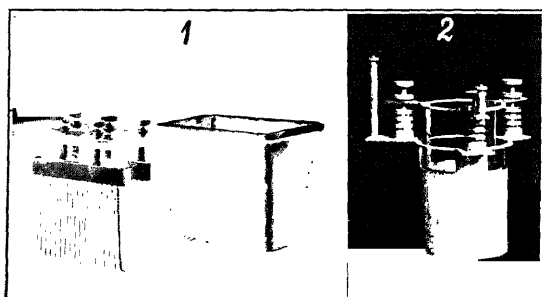


FIG. 29.—Apparatus for Testing the Power and Resistivity of the Oil.



of the resistance measured with a continuous potential after one minute of electrification is also plotted in the curve. It can be seen that the resistance at high temperature tends to become practically independent of the frequency and equal to that measured at D.C.

Heating the oil at high temperatures increases its dielectric losses ( $\cot \varphi$ ), as can be expected after what has been said about the resistivity. Another means of discovering the effect of the heating, in addition to the determination of the acidity and resistivity, is given by the measurement of  $\cot \varphi$ . Fig. 29 shows two sets of apparatus which may be used for these tests. The first is a condenser made up of a series of plates; the second is another condenser formed by two concentric cylinders. Both can be immersed in the oil to be tested and the power factor or the resistivity measured. The power factor, unlike the resistivity, is not affected by the dimensions of the condenser. The specific resistivity may easily be calculated, however, especially when the two condenser cylinders are used, from the dimensions of the condenser. The plate condenser is especially suitable for the dielectric loss test, as it has a sufficiently large capacity. Another instrument which can be used for comparison purposes, but only for the resistivity, is shown in Fig. 30. In this instrument, which is made of glass, the plates of the condenser are formed by two small electrodes. A heating coil is provided to heat the oil, and the resistance is measured by the ordinary methods.

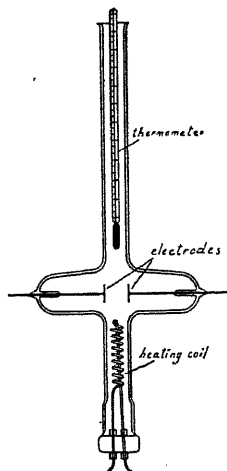


Fig. 30. Apparatus for the Measurement of the Resistivity of the Oil.

Up to this point we have supposed that the value of  $\cot \varphi$  is independent of the value of the difference of potential applied to the condenser. This, however, is only approximately correct, because if the electrical gradient in the oil is sufficiently high, the value of  $\cot \varphi$  changes. Fig. 31 shows the behaviour of a condenser made up of paper impregnated with a light mineral oil, and Fig. 32 that of a similar condenser,

but in this case impregnated with a thick mineral oil. The insulation thickness in both cases was 2 mm.

There are many reasons to believe that oils heated in contact with air show a variation of  $\cot \varphi$  with the voltage greater than those shown in Figs. 31 and 32.

### *Breakdown Strength.*

The breakdown voltage of oils when tested on samples sufficiently dried and clean does not alter very much for

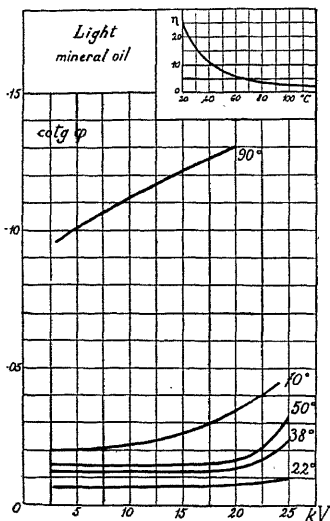


FIG. 31.

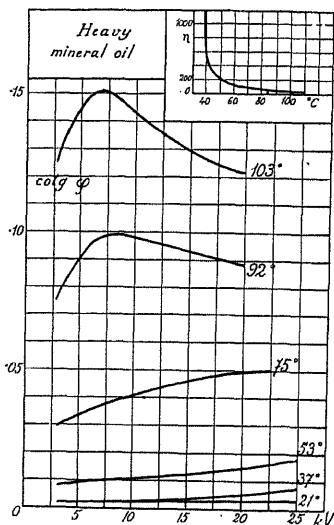


FIG. 32.

different qualities of oil. The effect of water and impurities and fibres which build up chains between the electrodes under the electrostatic forces is well-known and need not be mentioned here. Later, however, some reference will be made to the breakdown of paper impregnated with oil, as this, for the purposes of cable manufacture, is of the greatest importance.

Oil can be used for the impregnation of paper, either alone or mixed with resin. Resin increases the viscosity and makes a compound which adheres to the paper fibres, thus diminishing the danger of the compound draining towards the lowest parts of the cable.

# RESIN.

## General Information.

Resin is chiefly obtained by tapping trees of the lime family. The viscous liquid so obtained is distilled in order to extract all the light oils and turpentine, and the part which remains after distillation is colophony and is the resin generally used to add to the oil for cable impregnation.

Resin is divided into different classes according to colour; these range from white to a dark brown. Chemically, resin is constituted almost entirely of resinic acids, together with

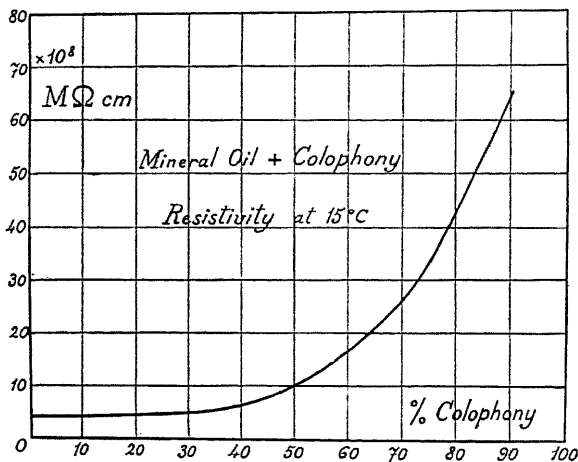


FIG. 33.

oxidised products. It commences to melt at 70° C. and gives a true solution in mineral oils.

## OIL-RESIN COMPOUND.

### Viscosity and Resistivity.

The properties of the oil-resin compound changes, of course, according to the percentage of each component. The viscosity increases to a large extent in proportion to the resin added, and the resistivity at low temperature increases with the increase of the percentage of resin. This is shown in Fig. 33, where the resistivity at 15° C. of a compound of mineral oil is plotted as a function of the percentage of resin. The electrical absorption is also greater when the percentage of resin is greater.

*Dielectric Losses.*

The dielectric losses are represented in Fig. 34 as a function of the temperature at different frequencies. The compound tested contained 35 per cent. resin.

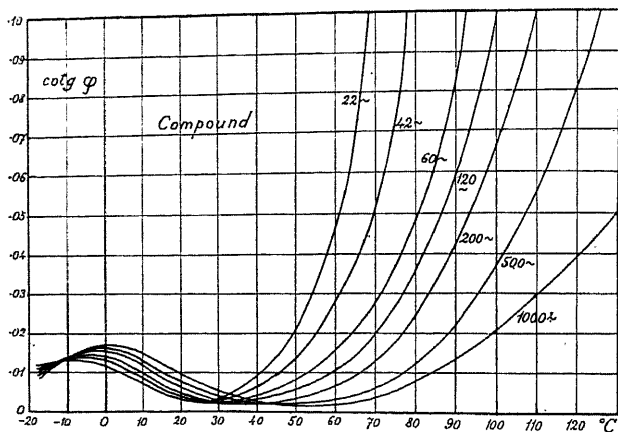


FIG. 34.

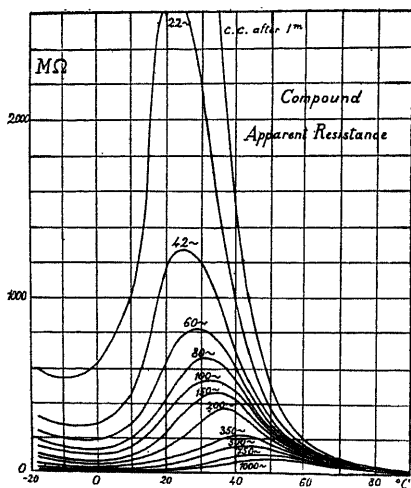


FIG. 35.

Fig. 35 shows the apparent resistance as a function of the temperature. It will be noticed that the resistance measured with D.C. at high temperature is not very different to the apparent resistance measured with A.C. This suggests that

it is probable, at least at high temperatures, that the conductivity of the compound is chiefly responsible for the dielectric losses.

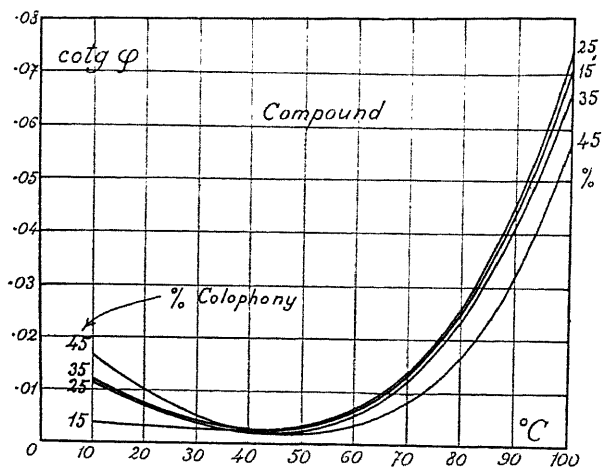


FIG. 36.

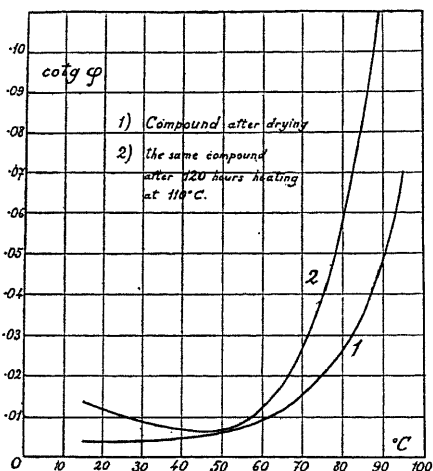


FIG. 37.

The value of  $\cot \varphi$  appears to vary at high or low temperatures according to the percentage of resin in the oil. When there is a greater percentage of resin this value increases at temperatures below 40  $^{\circ}\text{C}$ ., and seems to



diminish when the temperature is above 40° C. (see Fig. 36).

The effect of exposure to the air of this product when hot is similar to that of pure oils, that is, the value of  $\cot \varphi$  increases. This is shown by Fig. 37.

All the properties which have been mentioned correspond to small electrical gradients. At high gradients we meet with the same phenomena as is found in oils. The value of  $\cot \varphi$  is no longer constant, but depends upon the electrical gradient. At a low temperature, however, the power factor

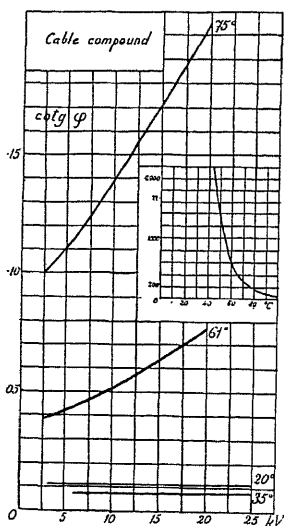


FIG. 38.

may be considered as being independent of the gradient. This is illustrated in Fig. 38, which shows the variation of  $\cot \varphi$  for different temperatures. The dielectric was 2 mm. thick and composed of paper impregnated with a mixture of mineral oil and resin. The viscosity is also shown in this figure as a function of the temperature.

#### THE IMPREGNATED PAPER.

##### *General Characteristics.*

Impregnated paper contains about equal volumes of paper fibres and oil or compound. The paper fibres, when dry, have a very high insulation resistance and low dielectric

losses when compared to oil or compound. It is to be expected, therefore, that the characteristics of impregnated paper, when referred to insulation and dielectric losses, are governed by those of the oil or compound. This is actually the case.

In the breakdown strength the fibres, on the contrary, play a very important part, as the dielectric strength of the impregnated paper is much higher than that of the oil

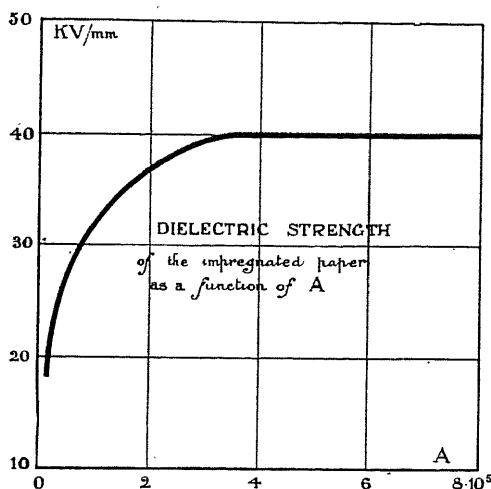


FIG. 39.

alone. This element, however, varies according to the quality of the paper used.

### *Breakdown Strength.*

Fig. 39 shows the relation between the dielectric strength and the impermeability (reciprocal of porosity) when the paper is impregnated with cable oil. The greater the impermeability of the paper the greater is its dielectric strength. The value of the dielectric strength, which can be obtained by prolonging the curve to cut the axis of the ordinates, may be considered as the dielectric strength of the oil alone. It does, as a matter of fact, correspond sufficiently well with that measured on pure oil, that is, without paper. Neither the effect of the temperature nor the change of frequency of the current alters the form of the curve.

It is very interesting to note that dry paper, that is paper impregnated with air, has a similar curve for its breakdown strength as a function of the impermeability, as is seen in Fig. 40. The value of the breakdown voltage is, of course, much lower than that of paper impregnated with oil.

It is also apparent that the only element which characterises the breakdown voltage of wood-pulp and manilla paper, of whatever origin, is the porosity. Papers composed of pure cellulose fibres have been considered here, but it is evident that any sizing of the paper may alter its

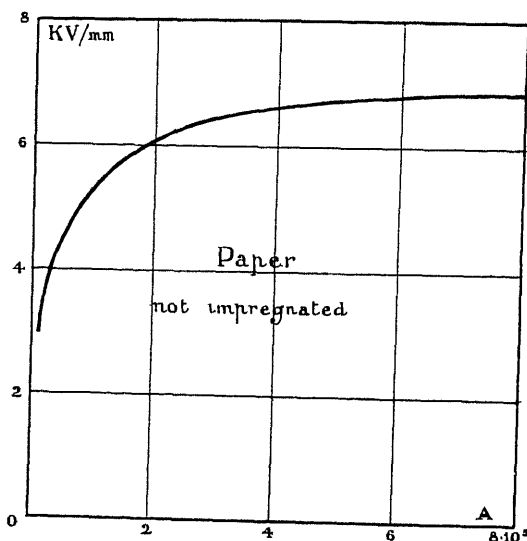


FIG. 40.

impermeability without increasing its dielectric strength. The hydrated cellulose, which forms during the refining and beating process of the paper by the hydration of the cellulose fibres, has the same effect as a glue sizing the paper. This substance is a sort of jelly which covers the fibres and seals the pores. As was stated in the first lecture, however, sizing and a too elaborate process of beating and refining must be considered as detrimental to the cable paper.

The form of the fibres seems to be of no consequence. Japanese silk paper, however, shows dielectric strength values much higher than those corresponding to its porosity.

A very interesting test which may throw some light on the

very complicated problem of finding a theory of the electric breakdown, at least for the particular case which is of interest to us, has been made by measuring the current flowing through the dielectric when a continuous potential is used.

If oil alone is tested and the current flowing through it is plotted as ordinates and the potential used (D.C.) as abscissæ a curve similar to that shown in Fig. 41 is obtained. The thickness of the dielectric was 4 mm. As can be seen, the Ohm Law is followed only for small gradients up to about 9,000 volts. For higher gradients the current increases very rapidly until the breakdown voltage is reached.

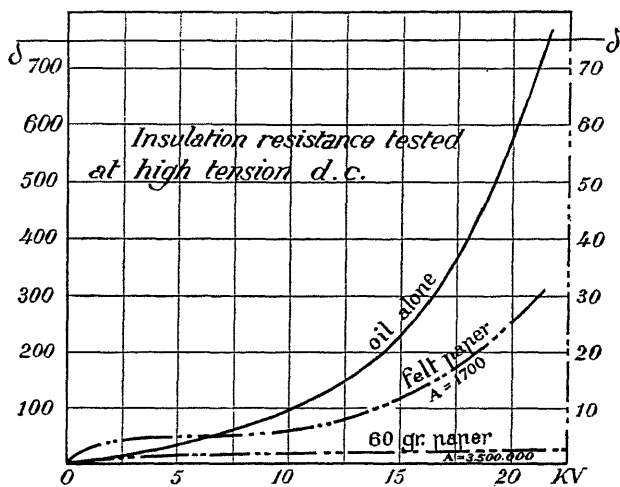


FIG. 41.

If the impregnated paper is substituted for the oil, the presence of the paper fibres seems to reduce the amount of current to an enormous extent, the reduction being larger the greater the impermeability of the paper used. In Fig. 41 the results of this test for papers of different qualities are shown, the current scale for the oil alone being given on the left, and that corresponding to the impregnated paper on the right of the figure.

A similar phenomenon is obtained by suspending a finely subdivided solid in the oil, such as colloidal caolin or French chalk. The same result can be obtained by adding carnauba wax, which is insoluble in the oil at low temperatures.

Fig. 42 shows a micro-photograph taken with polarised light, which shows the minute details of the wax suspended in the cable compound. Fig. 43 gives the result of a test made with a D.C. potential on a condenser composed of cable compound alone, and also another of the same test made on compound to which has been added 5 per cent. of the wax. The current flowing through the compound is enormously reduced by the presence of this small percentage of wax.

It is interesting to note that the difference between the two

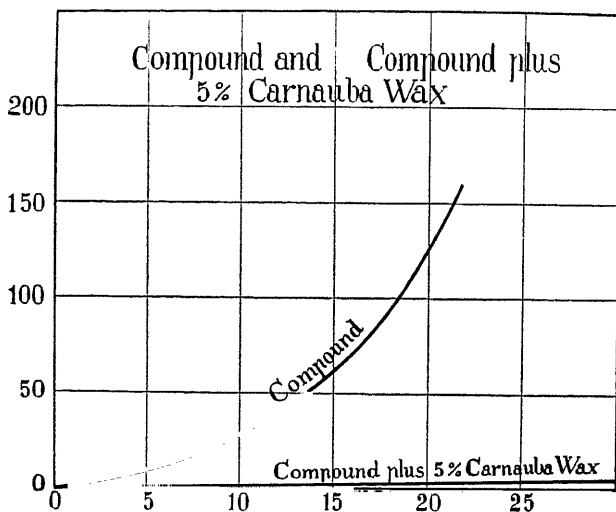


FIG. 43.

dielectrics disappears when the temperature at which the wax dissolves in the oil is reached.

It is quite probable that the effect of the paper fibres and that of the insoluble particles distributed in the oil are due to the same phenomena, which phenomena may be explained by a reduction in the mobility of the ions which carry the current through the oil.

Whilst the impregnated paper, from the point of view of the dielectric losses, deteriorates as the temperature becomes higher, it seems that there is a definite improvement when the dielectric strength is considered. This is shown in Fig. 44, which represents the dielectric strength of impregnated

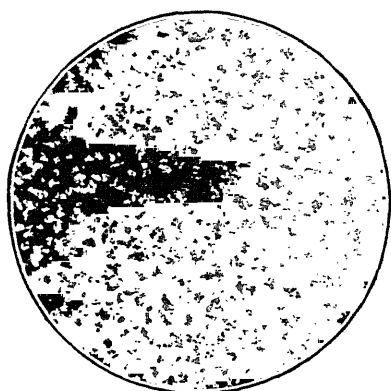


FIG. 42.—Microphotograph of Crystals of Carnauba Wax  
suspended in Cable Compound.

*To face p. 44.*



paper at different temperatures. Liquid dielectrics show a dielectric strength which increases according to the hydrostatic pressure to which they are subjected. The presence

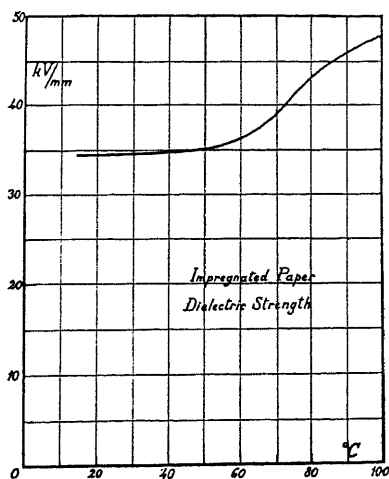


FIG. 44.

of the paper does not influence this property, as may be seen from Fig. 45. The pressures shown in the abscissæ are

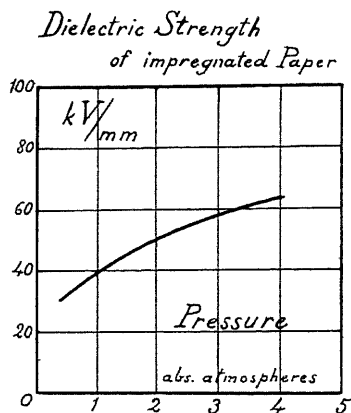


FIG. 45.

absolute atmospheres, the atmospheric pressure corresponding to 1.

The variation of the breakdown voltage with the hydro-



static pressure is often forgotten but, in cables, this variation is of great importance; as the pressure varies considerably, as will be shown later.

The frequency of the current used for the breakdown test is also of great importance, as the breakdown strength at low frequency is higher than that at high frequency. This, however, is common to all dielectrics. In Fig. 46 the values obtained on a paper impregnated with oil alone are given and also of compounds made up of 65 per cent. oil and 35 per cent. resin.

When tested at D.C. the dielectric strength is much greater. The values corresponding to those of Fig. 46 are 115 kv. for the A.C. and 135 kv. for the compound. When

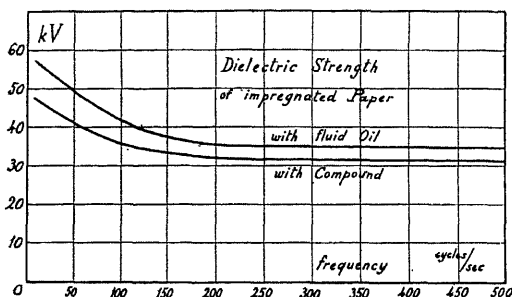


FIG. 46.

testing long lines of cable it is often impossible to make use of A.C. because of the large capacity current needed, which would necessitate the use of very powerful transformers. In these cases one makes use of D.C. high-tension voltage. As the breakdown strength of impregnated paper is higher for D.C. than for A.C., a suitable voltage is chosen: the value 2 to 2.5 times the r.m.s. value of the alternating voltage is generally used. It should be noted that the ratio between the D.C. rupturing voltage and that of the A.C. depends upon the quality of the dielectric and upon its temperature. Fluid oils show a smaller ratio than thick oils.

All the results indicated above refer to tests in which the rupturing voltage has been reached in a short time. If the time taken to reach a puncture is longer a lower breakdown voltage is obtained.

A curve connecting the breakdown voltage with the time taken to reach the breakdown is usually called the life curve of the dielectric. Fig. 47 shows the life curve for paper impregnated with cable compound. It represents the value obtained on condensers having a dielectric thickness of about 1 mm., but the voltages measured have all been reduced to the standard thickness of 1 mm. The curve starts with rather high values when the time of application of the voltage is short, but when this time is longer the breakdown strength diminishes until it reaches an asymptotic

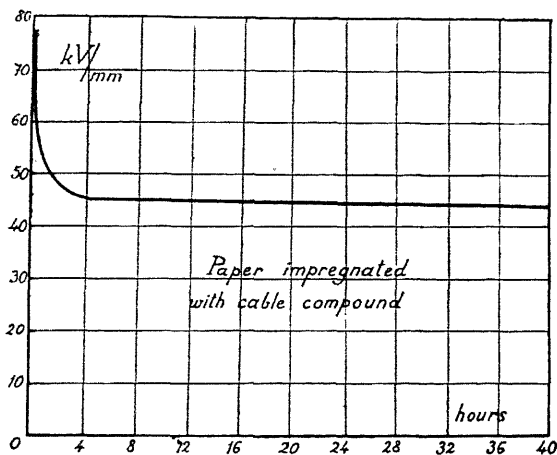


FIG. 47.

value. A tension less than this latter value can be applied to the condenser for an indefinite time without causing a rupture in the dielectric.

F. W. Peek has, from a large number of life tests, derived an empirical formula to obtain the gradient of the breakdown at any time. If  $g$  is the rupturing gradient at the time  $T$  of voltage applied :

$$g = g_s \left( 1 + \frac{a}{\sqrt[4]{T}} \right)$$

where  $g_s$  is the gradient corresponding to infinite time and  $a$  a constant. Both  $a$  and  $g_s$  change with the quality and thickness of the dielectric and with the frequency and temperature. The values which correspond to the curve

shown above do not, however, agree with the formula given by Peek.

A very interesting series of tests have been published by F. M. Clark. From these tests it appears that the breakdown voltage is effected by the preceding application of voltage, or, we might say, that if the application of the applied tension is stopped for a certain time this period of rest is of no importance, as the total time of application of voltage taken to reach the breakdown is independent of the rest. Similar tests have been made on actual cables, and the results have been identical. It appears that profound deterioration takes place in the dielectric under the electric

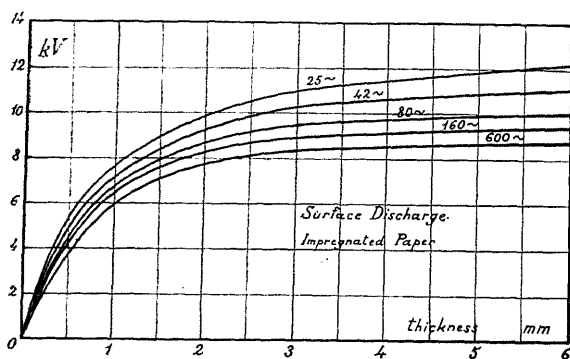


FIG. 48.

stresses and, after a certain time, these deteriorations become such that breakdown occurs.

The following information regarding the surface discharge is of certain interest in connection with what will be said on the distribution of the field in three-phase cables. Fig. 48 shows the relation between the length of the discharge and the corresponding voltage at different frequencies. The surface on which the discharge took place was that of a sheet of paper immersed in a cable compound, the field being uniform. This was realised by placing a pile of sheets of paper, having a total height equal to the length of the discharge to be obtained, between the two electrodes. In the pile of sheets of paper, parallel to the direction of the electrical stress, a slit was cut and completely filled with compound under vacuum in order to avoid films on the surface to be tested.

The shape of the curve is very remarkable as it proves that after a certain length it is practically useless to increase the length of the gap to appreciably increase the discharge voltage.

Similar curves to these are useful in connection with the design of junction boxes, in which stresses parallel to the surface of the paper come into play to a great extent.



## LECTURE III



## LECTURE III

### THE ELECTROSTATIC FIELD

#### *General Information.*

THE fundamental problem in the design of a high-tension cable is that of obtaining a sufficient dielectric strength between the conductors and between each conductor and the lead sheath. We have already seen how the impregnated paper behaves when tested for breakdown strength under different conditions of temperature and pressure of the voltage and time of application.

All these tests have been made on sheets of impregnated paper of various thicknesses and between flat electrodes, so that the electric field may be considered as being uniform. Under these conditions the breakdown voltage is a maximum, for the same thickness of insulation may be punctured at a lower voltage if the field is not uniform.

A simple theory of the breakdown when the field is not uniform is that the insulating material fails when there is established at any point in it a gradient of voltage equal to that which produces the breakdown in a uniform field. This theory, of course, implies that in a uniform field the breakdown gradient is not dependent upon the thickness of insulation; this, however, is not true.

Unfortunately, owing to the lack of exact knowledge of the mechanism of breakdown of liquid and solid dielectrics, this simple theory, although recognised as being not absolutely true, is the only one available.

It is therefore necessary to know the distribution of potential in the dielectric. Mathematical methods offer assistance only in the few cases where the fields are comparatively simple: in the majority of cases the difficulties presented by mathematical analysis make this method practically useless.

#### *The Field in Single-Core Cables.*

One of the cases where mathematical methods offer a solution is that of the field between two concentric cylinders



which corresponds to that of a single-core cable. Although this question is widely known, it will be useful to recall briefly some of its principal points.

The equipotential surfaces, by symmetry, must be cylindrical, having circular sections concentric with the electrodes.

The electrostatic force at any point is inversely proportional to its distance from the centre since the flux is constant through the equipotential surfaces.

If we call  $F$  the electrostatic force at a point distant  $x$  from the centre, and  $F_0$  that corresponding to a point on the surface of the internal cylinder which has a radius  $x_0$ , we have

$$Fx = Fx_0$$

but we can also write

$$F = - \frac{dv}{dx}$$

$\frac{dv}{dx}$  being the differential of the potential with respect to  $x$  at the point considered, or the electrical gradient as it is called, at  $x$ .

We then have

$$- \frac{dv}{dx} x = F_0 x_0$$

Integrating this equation between the limits  $x_0$  and  $x_1$  ( $x_1$  being the radius of the outside cylinder), we have :

$$V_0 - V_1 = F_0 x_0 \log_e \frac{x_1}{x_0}$$

where  $V_0$  and  $V_1$  are the potentials of the two surfaces.

If we call  $v$  the difference between  $V_0$  and  $V_1$  and rearrange the formula we have the well-known expression of the gradient at the surface of the inner conductor.

$$F = \frac{v}{x_0 \log_e \frac{x_1}{x_0}}$$

as  $F_0 x_0 = Fx$ , we can immediately write the gradient at any point,  $x$ .

$$F = \frac{v}{x \log_e \frac{x_1}{x_0}}$$

From this expression we are able to calculate the electrostatic force at any point of the dielectric. If we plot the radii of the different points of the dielectric as abscissæ, and the value of  $F$  as ordinates, we obtain a curve similar to that shown in Fig. 49. The maximum value of the gradient is, of course, near the inner electrode, whilst the minimum is nearer the outer.

It is of interest to investigate how  $F_o$  changes when the radius of the internal cylinder varies and that of the outer is kept constant.

When the values of  $x_o$  are very small, those of  $F_o$  are very large, but upon increasing  $x_o$ , then  $F_o$  rapidly diminishes. If, however, the value of  $x_o$  is made to approximate too closely the value of  $x_1$ ,  $F_o$  again increases.

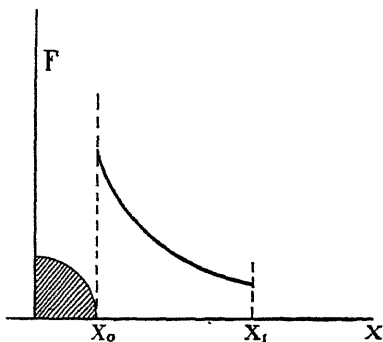


FIG. 49.

It is interesting to ascertain the value of  $x_o$  which corresponds to the minimum value of  $F_o$ . This can be obtained in the usual way by differentiating  $F_o$  with respect to  $x_o$ , and equating to zero. We obtain :

$$\log_e \frac{x_1}{x_o} = 1$$

That is to say that the ratio  $\frac{x_1}{x_o}$  must be equal to  $e$ , the base of the natural logarithms (2.718).

The electrostatic force or the electrical gradient in this case becomes :

$$F_o = \frac{v}{x_o}$$

### *The Electrolytic Method.*

Whilst the field in a single-core cable corresponding to that existing between concentric cylinders is easily calculated, that corresponding to other types of cable offers great difficulties from the mathematical point of view, and a solution has been sought for in an experimental way.

Among the different methods available the one which offers the greatest degree of accuracy and simplicity is that known as the electrolytic method. It is based on the fact that an electrostatic field may be produced by a current flowing through a conductive medium. If electrodes are immersed in an electrolyte and a difference of potential is applied, the distribution of the potential in the electrolyte is the same as that which would take place in the medium if the electrolyte were substituted for a dielectric. This, of course, is supposing that the medium occupied by the electrolyte is large when compared with the dimensions of the electrodes and their distance apart.

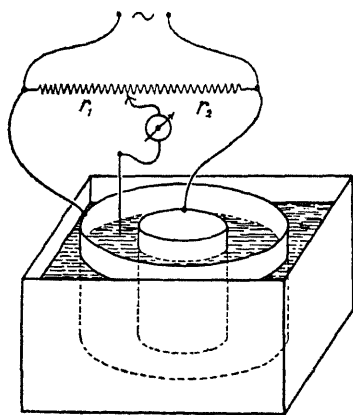


FIG. 50.

In many cases, however, it is possible to reduce the volume of the electrolyte, either because the field to be explored is totally surrounded by one of the electrodes or because of the existence of planes of symmetry. For instance, in the case of a field included between two concentric cylinders the test can be made as follows (see Fig. 50) :

Two concentric metallic cylinders are immersed in a non-conducting tank containing the electrolyte. As the tank is non-conducting, the flow of the current between the two electrodes is limited by two planes perpendicular to the axis of the cylinders, one plane being represented by the bottom of the tank and the other by the surface of the electrolyte. Of course, any plane perpendicular to the axis of the cylinders is a plane of symmetry, and the propagation of the current and the resulting distribution of potential remains unaltered if the conducting medium is cut by any such plane.

In a similar way the field existing in a three-core cable may be represented by means of a model.

In the simple case of a single-core cable the field may be explored as shown in Fig. 50. The source of e.m.f. con-

nected to the two electrodes is also connected to a group of two resistances in series,  $r_1$  and  $r_2$ . A needle, which is made of conducting material and can be immersed in the electrolyte, is connected to the centre point of the two resistances through a galvanometer. Either one of the two resistances or the position of the needle can be changed so that no deflection is obtained in the galvanometer. The position occupied by the needle and the centre of the two resistances are then both at the same potential and the potential at that point of the electrolytic bath can be immediately calculated from the value of the two resistances.

It is quite clear that the needle should be parallel to the axis of the cylinders and small enough not to alter the electric field. Owing to the polarisation of the electrodes, D.C. is not suitable for such tests; high frequency A.C. is also unsuitable owing to capacity effects. A.C. of industrial frequencies seem to be the most suitable. The electrodes should be kept perfectly clean when accurate results are required.

It is not necessary for the model to have the same dimensions as those of the corresponding cable because, as can easily be demonstrated, models having dimensions which are geometrically similar give a distribution of the equipotential surfaces which is also geometrically similar.

#### *The Electrostatic Method Applied to a Three-Core Cable.*

The field in a three-phase cable has been examined according to this method, using a three-phase supply of current.

What we wish to obtain is a picture of the field at different instants of the period, and a method which does not necessitate the use of three-phase current may be employed in the following way: We can apply to the electrodes of our model potentials corresponding to the instantaneous values of the three-phase potentials at the particular instant of the period we wish to study.

As, for the reason stated above, it is desirable to use A.C. instead of D.C., it is possible to solve the problem of producing the e.m.f. required by this simple method.

A phase shifter is connected by one phase to the electricity supply. The e.m.f.s. generated in its three secondaries are equal in phase and their values are equal to the

projection on a straight line of three vectors having the same length, but a displacement of 120 degrees with respect to each other.

This is exactly what we need to feed our model. The different instants of the period are obtainable by changing the position of the three secondaries, *i.e.*, by turning the control-wheel of the phase shifter.

The circuit is arranged as shown in Fig. 51. The centre of the three secondaries is connected to the outside cylinder and to the variable resistance between this centre and one electrode. The exploring needle is connected to the variable point of the resistance by means of an electro-dynamometer,

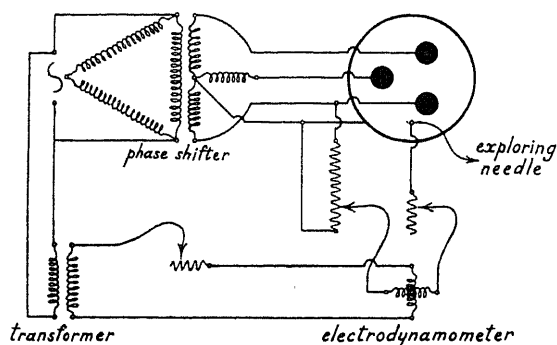


FIG. 51.—Circuit used to determine the Field in a Three-phase Cable by the Electrostatic Method.

the fixed coils of which are fed directly by the source of energy.

It will not be necessary to describe the very simple arrangement, by means of which the position of the needle may be graphed, but the results are given (Fig. 52). The field, as obtained from the model, is shown for seven instants of the period at intervals of 5 degrees (Fig. 52).

The equipotential lines correspond to the potentials 0.1, 0.2, 0.3, 0.4, 0.5, etc. It is easily seen that it is sufficient to explore a part only of the period including 30 degrees, because, owing to the symmetry of the potential and of the model, all the other parts of the period may be easily deduced.

Fig. 52 shows also two particular fields, the first corresponding to the case in which two conductors of the cable are

connected together and the third to the lead sheath ; the second field is where two conductors are connected to the sheath and the other insulated. These two cases are important because it is usual to test three-core cables by applying the testing voltage to one core only, the other two being connected to earth. Another frequent test is that in which the three cores connected together are tested against the lead sheath.

By experimenting on models which have a different ratio between the diameter of the three electrodes representing

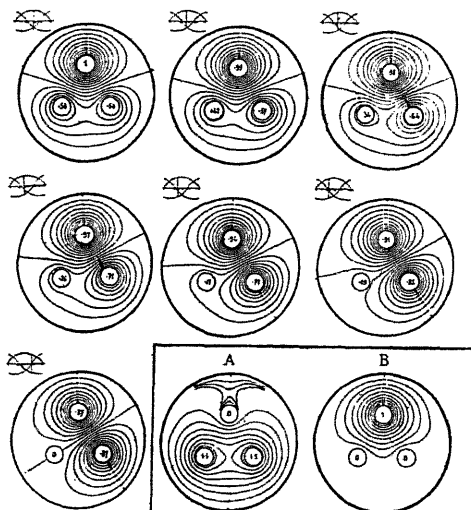


FIG. 52.—The Field in a Three-phase Cable at different times of the period.

the conductors and the lead sheath, it has been possible to obtain the distribution of the potential in cables having different copper sections and insulating thickness and the important particulars affecting the design of a cable can be deduced from them. The voltage gradient at definite points may be deduced from the figures representing the field in a very simple manner by dividing the difference of potentials between two equipotential surfaces by their distance at a considered point. In this way it has been found that the maximum gradient in the cable occurs near the conductor on the lines which connect the centre of the conductor to the other two.

Owing to the fact that the equipotential lines do not coincide with the surface of the insulation on the cores and belt, there is a potential gradient which is tangential to these surfaces, and this may produce superficial discharges. The maximum gradient tangential to the surface of the core occurs in the small curvilinear triangle between the cores (see Fig. 53).

Other important potential gradients occur at the point of

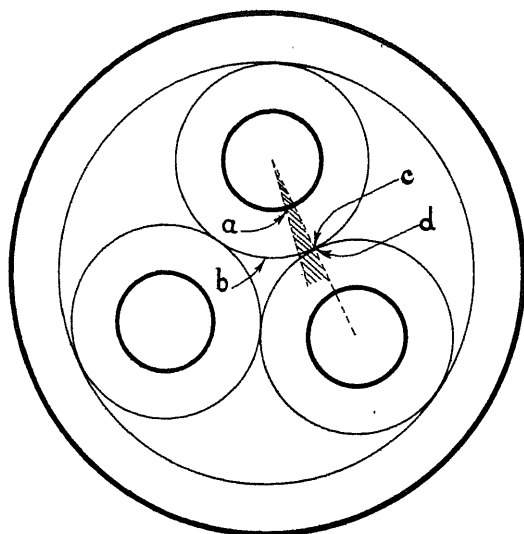


FIG. 53.

tangency of the two cores. All these gradients, as obtained by means of the electrolytic model, are given in Figs. 54, 55 and 56, in which *a* is the maximum radial, *b* the maximum tangential, *c* the radial at the point of tangency of the cores, and *d* the tangential at the same point (as shown in Fig. 53).

In each one of the curves the abscissæ are the values  $\frac{s}{d}$  of the dielectric thickness between conductors and between conductor and lead divided by the diameter of the conductors. The ordinates are the ratio of the gradient we wish to determine to the average gradient, *i.e.*, the voltage existing between conductors divided by the thickness of the

insulation. It is easy to see that curves plotted in this form may be used for any cable, provided the thickness between conductors and between conductors and lead is equal.

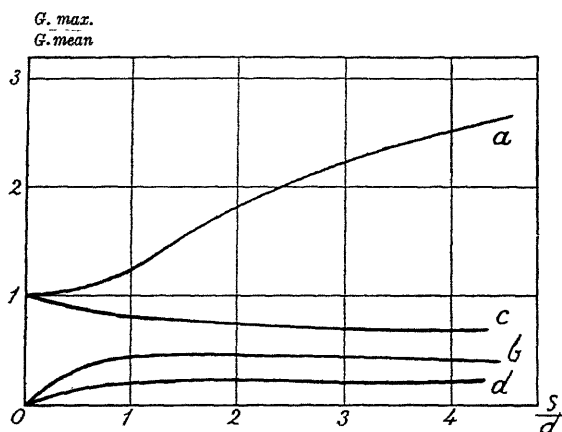


FIG. 54.—Gradients of a Three-phase Cable.

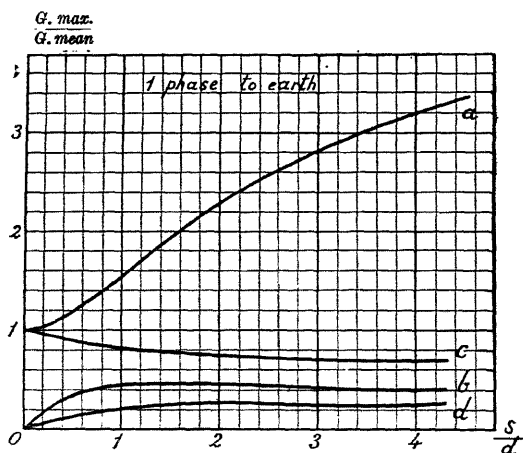


FIG. 55.—Gradients of a Three-phase Cable.

Fig. 54 refers to a three-phase field and gives values of the different gradients as indicated by Fig. 53. Fig. 55 corresponds to a three-phase field, but with one phase earthed. Fig. 56 refers to a single-phase field in which the tension is



applied to one conductor, the other two being connected to the lead sheath.

The tangential stresses in a belted cable are of the same order as the radial stresses, whilst the resistance of impregnated paper to breakdown is, on the contrary, much greater when the paper has to withstand the tests across its thickness than when its surface is stressed.

It is thus easy to understand why cable manufacturers are forced to use a dielectric having a greater thickness than that required to withstand radial stresses, because the tangential stresses must also be taken into account.

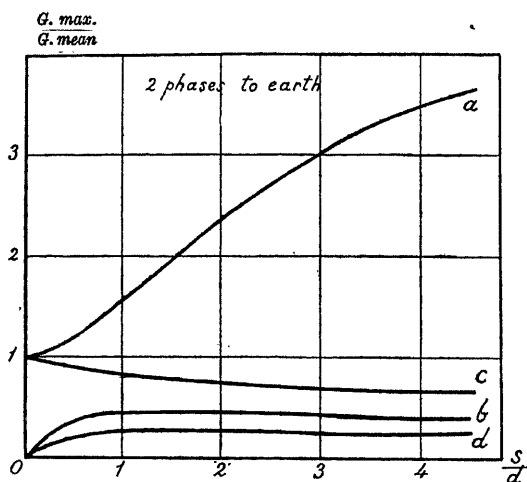


FIG. 56.—Gradients of a Three-phase Cable.

For this and other reasons the ordinary belted type of cable for high-tension working is more expensive, and not as safe as cable formed by three single-core cables stranded together. Consequently two other types of construction are generally preferred, one being the type made by assembling together three cores, each of which is externally screened with a conductive tape and the other composed of three single-core lead-covered cables stranded together (see Fig. 5, Lecture I.). The conductive tape in the first of these types is connected to the lead electrically, so that the cable is nothing more than an assemblage of three single-core cables. The conductive tape in question may take the form of a metallic strip or a paper coated with a thin sheet of aluminium.

*Other Applications of the Electrostatic Method.*

Returning to the electrostatic method of investigating the electrostatic field in a cable, it is interesting to show how curves can be deduced to calculate the capacity of a three-phase cable—it is well-known that mathematically this problem is rather complicated.

The problem of calculating the capacity of a condenser is to ascertain the charge built up on one plate when the applied potential is known.

The charge on one plate can easily be found when the electrostatic force  $F$  at the different points of its surface is known. If at a point the density of the charge is  $\sigma$  and  $F$  is the electrostatic force just outside the point, we have the well-known relation

$$F = 4\pi\sigma$$

If  $ds$  is an element of the surface of the conductor

$$Q = \int \sigma ds = \int \frac{F}{4\pi} ds$$

If we call  $n$  the perpendicular distance between the plates

$$F = -\frac{dv}{dn}$$

and

$$Q = -\frac{1}{4} \int \frac{dv}{dn} ds$$

The method as it is actually used in practice is as follows :

Let us consider an equipotential surface which is very near the surface of the conductor. The difference of potential between the two surfaces is  $\Delta v$ . The surface of the conductor is divided into small equal parts,  $\Delta s$ , and the distances,  $\Delta n$ , between the equipotential surface and that of the conductor is measured.

The quantity

$$\frac{1}{4\pi} \Delta v \Delta s \approx \frac{1}{\Delta n}$$

represents the value of  $Q$ . The smaller the elements into which the surface has been cut and the smaller the distances,  $\Delta n$ , the greater is the accuracy of this value.

Another consideration which may help in the actual cal-

ulation is the following : A condenser may be considered as being formed of a number of condensers in series, the plates of which are represented by the equipotential surfaces of the field.

As the condensers are connected in series, the charge on each plate is constant and equal to that on the conductor. We may, therefore, choose in the graphic representation of the field two surfaces which are most suitable for the approximation mentioned above, and use for them the formula written above.

The curve represented in Fig. 57 has been drawn accord-

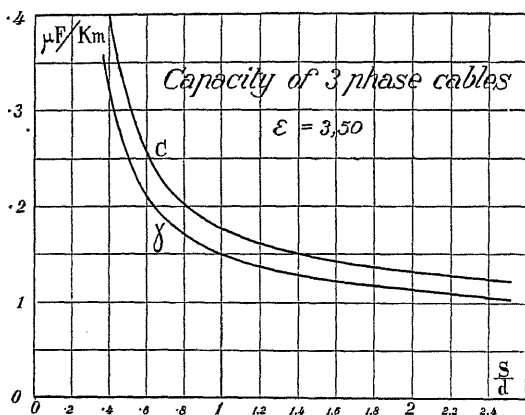


FIG. 57.

ing to this method, and can be used for ordinary belted cables.

The value  $\frac{S}{d}$  (insulation thickness divided by the diameter of the conductor) is plotted as abscissæ, and the capacity of one core against the other two and the lead as ordinates expressed in microfarads per 1,000 metres.

The value obtained from the drawings of the electrostatic field have been multiplied by 3.50, which is an average value for the specific inductive capacity of the impregnated paper forming the dielectric of the cable.

The capacity of one conductor against the other two connected to the lead sheath is represented by the curve marked

a. The curve marked C gives the capacity which serves to calculate the capacity current per 1,000 metres of cable when it is working with a three-phase voltage.

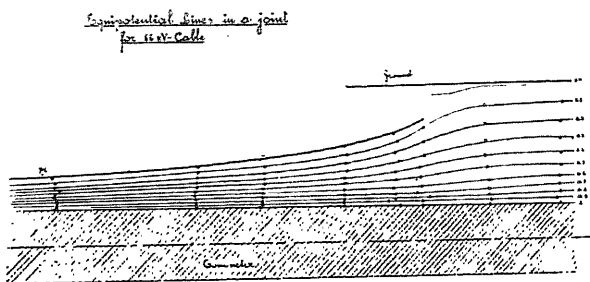


FIG. 58.

From this capacity,  $C$ , the charging current,  $i$ , for 1,000 metres of cable can be derived from the formula :

$$i = 2\pi f C \frac{V}{\sqrt{3}}$$

where  $V$  is the voltage between phases and  $f$  the frequency. The capacity per mile can be obtained by multiplying the capacity per 1,000 metres by 1.6.

The electrolytic method is very useful for the investiga-

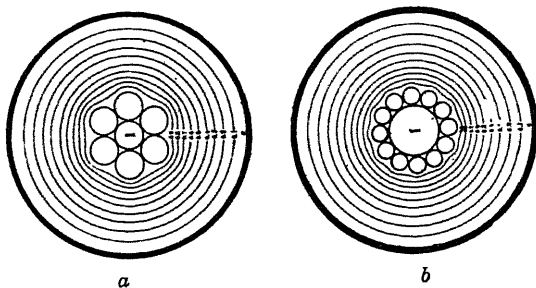


FIG. 59.—Electrostatic Field around a stranded conductor.

tion of other types of field which are of interest in cable study.

Fig. 58 shows the field in a single-core joint as obtained by the electrolytic method.

Fig. 59 shows the field around two stranded conductors

having a different number of wires, and Fig. 60 the gradient deduced from Fig. 59 (a) compared with that of a cable

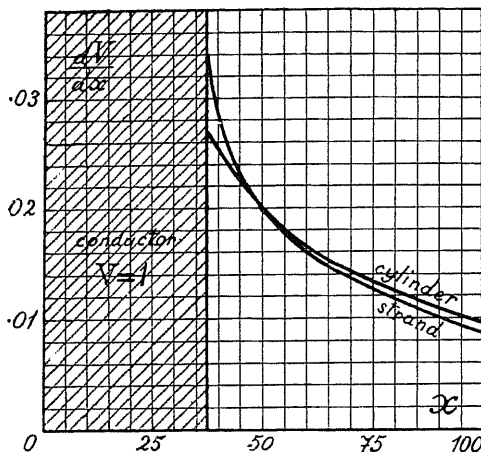


FIG. 60.—Gradient in a Single-core Cable corresponding to Fig. 59 (a).

having a solid conductor with the diameter of the circle circumscribed to the strand.

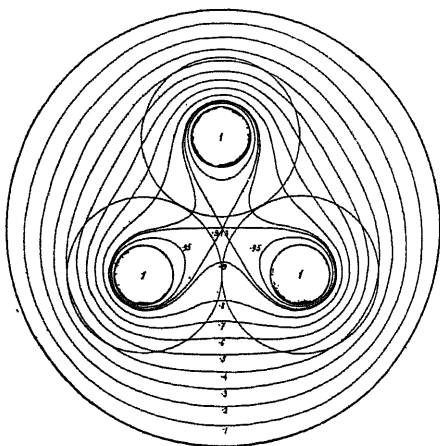


FIG. 61.—Field in a Three-core Cable; the three condensers at the same potential.

Fig. 61 shows the electrostatic field of a three-phase cable where all three conductors are at the same potential, but differ from that of the lead. This figure may be used to

calculate the electrostatic capacity of the three conductors connected together, against that of the lead, and may also be used to calculate the temperature at which a three-phase cable is working when in service.

The equipotential surfaces, as a matter of fact, also represent the isothermal surfaces. The voltages have simply to be replaced by the temperatures.

The amount of heat which is given out of a three-phase conductor may be calculated as follows :

If we consider an isothermal surface near the lead the

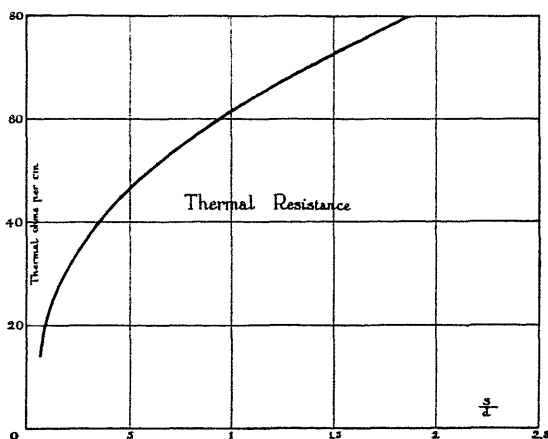


FIG. 62.—Thermal Resistance of Three-core Cables.

amount of heat entering a small part,  $\Delta s$ , of the inner surface of the lead can be calculated as follows :

The temperature  $t$  of the isothermal surface differs from that of the lead by  $\Delta t$ . The amount of heat passing from this surface to that of the lead for this small surface is :

$$\Delta w = \frac{1}{\sigma} \frac{\Delta t}{\Delta n} \Delta s$$

$\Delta n$  being the distance from the lead of the isothermal considered and  $\sigma$  the thermal resistivity of the impregnated paper.

The total heat,  $w$ , entering the lead, if equal portions of the surface are considered, will be :

$$w = \frac{1}{\sigma} \Delta t \Delta s \sum \frac{1}{\Delta n}$$

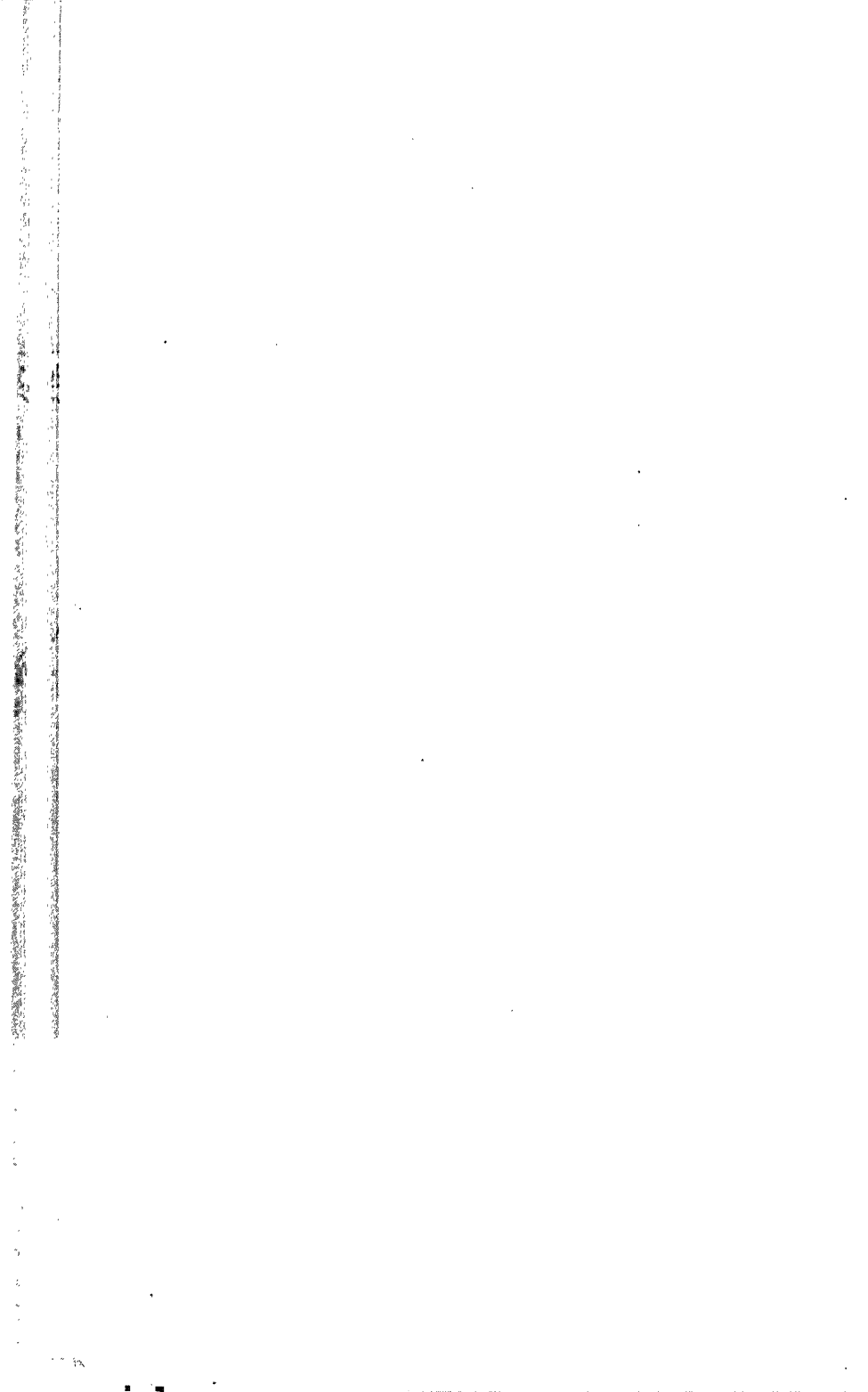
If  $w$  is known, the thermal resistance of the cable is also known by dividing the total temperature by the number of watts dissipated in the conductors.

Fig. 62 gives the values of the thermal resistance in the insulation of three-core cables, expressed in thermal ohms per metre of cable. The assumed value of  $\sigma$  is 750. The

value of  $\frac{s}{d}$  is plotted as abscissæ (insulation thickness divided by the diameter) and the thermal resistance as ordinates.

## LECTURE IV





## LECTURE IV

### THE DIELECTRIC OF A CABLE CONSIDERED FROM THE POINT OF VIEW OF ITS IMPREGNATION

#### *The Impregnation Process.*

IN order to understand the mechanical and electrical properties of high-tension cables, it will be helpful to give a brief description of the impregnating process.

As explained in the first lecture, when the drying process is considered to be finished the cable is kept under vacuum for a certain time, after which insulating compound is allowed to flow into the tank. The cable is surrounded by compound which does not commence to enter the paper of the cable until the vacuum is broken and atmospheric pressure, acting on the surface of the compound, forces it through. At first the pressure forcing the compound into the cable is the difference between atmospheric pressure and that which corresponds to the degree of vacuum which it has been possible to establish within the cable. After a certain time the compound penetrating the cable insulation reduces the volume left to be impregnated and consequently the pressure of the gas contained in the insulation is increased. When this pressure becomes equal to that due to the atmosphere acting on the surface of the compound a state of equilibrium is reached.

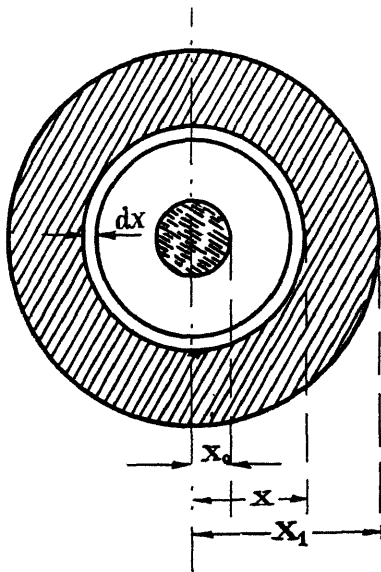


FIG. 63.

The quality of the impregnation depends upon the degree of vacuum which has been obtained in the cable before the compound is admitted to the tank.

It is possible to calculate the time taken to impregnate a cable in the following manner.

Let us consider a single-core cable (Fig. 63) in which the conductor has a radius  $x_0$ , and the insulation a thickness such that the total radius of the core is  $x_1$ . Let us suppose also that at a certain time  $t$ , the compound which enters the cable to impregnate it has reached a depth corresponding to a radius  $x$ . The time  $dt$  taken to impregnate a further depth of insulation corresponding to a thickness,  $dx$ , can be calculated when the resistivity  $A$  of the paper and the viscosity of the compound are known. If we call  $R$  the resistance opposing the flow of compound by the depth of insulation comprised between the radii  $x$  and  $x_1$ ,  $P$  the pressure inside the cable, and  $P_1$  the pressure acting on its external surface, then

$$dt = \frac{2\pi k x dx R}{P_1 - P}$$

Where  $2\pi k x dx$  is the volume of compound contained in the insulation comprised between  $x$  and  $x - dx$  and  $k$  is a constant, less than unity and equal to the ratio of the volume of compound to the total volume, i.e., paper fibres plus compound.

$R$  is a function of  $x$  and  $x_1$ , and is proportional to  $A$  and  $\eta$ .  $P$  also is a function of  $x$  and  $x_1$ , because  $P$  may be obtained from  $P_1$  by considering that the volume occupied by the gas (at the beginning of the impregnation) which corresponded to the radius  $x_1$  has been reduced to that corresponding to  $x$ . We can therefore write that  $dt$  is some function of  $x$ ,  $x_1$  and  $P_1$  thus :

$$dt = A\eta k \int (x, x_1, P_1) dx.$$

This expression can be integrated, and, extended between the limits  $x_1$  and  $x_0$ , gives the time taken for the complete impregnation of the cable. As a matter of fact the time corresponding to the limits indicated above is infinite, but the time corresponding to limits very near those indicated may be calculated by using the ordinary methods of approximation.

The time  $t$  for the impregnation will, of course, be pro-

portional to  $A$ , to  $\eta$ , and to  $k$ . It is also evident that an increase over the atmospheric pressure of  $P_1$  will reduce  $t$ .

To reduce the time  $t$  it is necessary to operate at a high temperature so as to reduce the viscosity  $\eta$  of the compound as much as possible. It is possible to reduce the impermeability  $A$  of the paper for the outer part of the cable where the electrical gradient is small enough to permit such reduction. Some manufacturers increase the pressure acting on the compound during impregnation.

The theory of the impregnation is, however, much more complicated than that outlined above because many other factors come into play, some of which have the effect of slowing down the impregnation and making it poorer, while others speed it up and improve it.

The compound contains a certain amount of gas in solution, part of which is set free as soon as the compound enters the vacuum tank. This amount, however, is not usually sufficient to agree with the Henry Law for the well-known phenomena of supersaturation, and consequently a certain amount of gas remains in the compound. When this enters the paper a state of great subdivision is created and a further amount of gas is liberated. The gas which is set free increases the pressure in the cable and reduces the speed of flow of the compound through the paper and thus decreases the degree of impregnation.

In order to avoid this trouble practically all manufacturers do their best to degasify the compound before it is admitted into the impregnating tank. It has already been explained how this can be done and the type of machine which can be used has been shown.

When the impregnation is finished the pressure in the cable should be that of the atmosphere. The compound, which has lost a great deal of the gas which it contained in solution, now absorbs it again, but it is not an easy matter to state to what extent this occurs.

Some manufacturers make use of this phenomenon to improve the impregnation and use a gas more soluble in the compound than air to create an atmosphere in the cable before commencing the impregnating process.  $\text{CO}_2$  is the gas used.

A factor of great importance in the impregnation process is

the ability of the paper to absorb oil. As has already been seen, this absorption can be measured and expressed as a pressure exerted by the paper on the oil. The figure which represents this pressure can eventually be used for calculation. The most important point is, however, that as soon as the compound comes in contact with a layer of paper the compound spreads from this point on to the whole sheet, being attracted by the absorption pressure. How this phenomenon controls the impregnation of a three-phase cable is of great interest.

In Fig. 64 the first illustration shows a section of three-phase cable before impregnation, the second when the com-

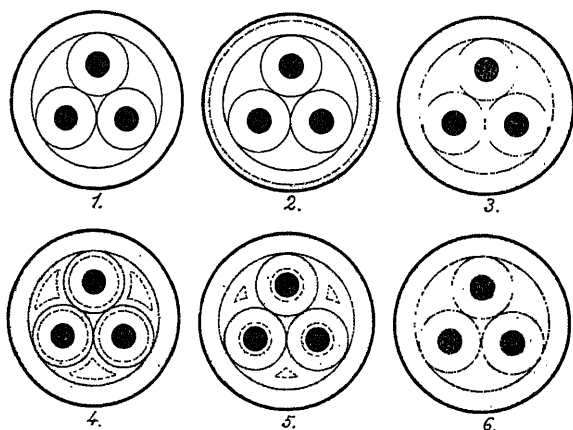


FIG. 64.

pound has entered a portion of the belt, and the third when the whole of the belt has been impregnated.

Up to this moment the compound has penetrated the insulation uniformly in concentric circles, the paper sheets being laid in concentric circles, but as soon as the compound reaches the cores and fillings, the propagation entirely changes its form and continues according to circles which are concentric with the individual cores or to curves which are concentric with the fillers. This is shown in 4 and 5 of Fig. 64, whilst 6 of the same figure represents the cable when the impregnation is completed.

The phenomenon described is due to the fact that as soon as the compound reaches the surface of a core it is attracted

by the paper tapes and travels along them, thus completely surrounding the core.

Let us imagine that at a certain point of the insulation two layers of paper are in contact—not along the whole surface, but only at certain points. It is evident that the compound travels through these points of contact from one sheet to another according to the phenomena just explained, and will spread along the whole sheet before it can be reached by the compound at other points, not in contact. It is clear that in this way a certain quantity of gas is trapped between the two paper sheets, which explains how gaseous films can remain distributed all through the insulation. These films occur, of course, to a greater extent where the space between the sheets of paper is greater, or where cavities are left in the paper—for instance, where there is a wrinkle. It is difficult, in the same way, to ensure a perfect contact between cores and fillers of a three-phase cable, with the result that a film of gas may very easily be formed at these places, and the entire efforts of the cable maker to obtain a good three-phase high-tension cable have been centred in the direction of ensuring a good contact between cores and fillers.

As previously explained, the compound is admitted into the vacuum tank when hot to diminish its viscosity. When the impregnation is completed the cable is allowed to cool down in its own compound, and as during this period the compound contained in the cable contracts, a further quantity of compound enters the cable. Without this precaution empty spaces might easily be formed.

Cable manufacturers have studied these details very carefully and have improved their impregnation methods to such an extent that the dielectric of a cable now contains a very limited volume of gas.

#### *The Effect of the Thermal Expansion of the Compound.*

What has hitherto been said holds good until the moment when the cable goes into the lead press to be sheathed, but it is no longer the case if the cable, after the lead sheathing, is allowed to cool down to a temperature lower than that existing when it was taken from the lead press.

The thermal expansion coefficient of the impregnating material may be considered as practically equal to eight

ten-thousandths for  $1^{\circ}\text{C}$ . That of the copper and the paper are both very small when compared with that of the oil, as the following figures show :—

Oil . . . . .	0.0008
Copper . . . . .	0.00005
Fibres . . . . .	0.00009

When the lead sheathing becomes heated it expands and the volume contained in it also expands. This increase of volume, however, is far from being sufficient to correspond to the increase of volume of the compound. An example will show more clearly and definitely the order of the quantities concerned.

A three-core cable with a copper section of 0.20 sq. in. and suitable for a working pressure of 25,000 volts, has a diameter of about 68 mm. under the lead sheathing and a volume of compound about 16 c.c. per centimetre length. If we diminish the temperature of the cable by  $20^{\circ}\text{C}$ ., the volume of the compound diminishes by about  $20 \times 0.0008 \times 16 = 0.256$  c.c. To this we must add the amount of contraction of the copper and paper fibres, and we obtain a total of 0.289 c.c.

The decrease of volume due to the contraction of the lead sheath, however, for the same diminution of temperature, is only 0.076 c.c. The difference between 0.289 and 0.076, *i.e.*, 0.213 c.c., may be called the apparent contraction of the compound.

Let us first suppose that the lead is absolutely non-elastic, and also that the paper has no elasticity when compressed. Let us further suppose that there is no gas in the cable nor in solution in the oil, and that its vapour tension is very low. It is then clear that the consequence of the reduction of temperature is the formation of a perfect vacuum in the cable and that 0.213 c.c. will remain absolutely empty. This condition, however, can never occur, because the different parts of the cable are never in the state mentioned above. The presence of gas free and in solution, the elasticity of the lead and perhaps that of the paper, tend to reduce the degree of vacuum and of the volume which remains empty. The elasticity of the lead and the paper is,

however, very low, and the factor which seems to play the most important part in reducing the degree of vacuum is the amount of free gas in the cable.

This is a very interesting point, from which it can be deduced that a cable having a poor impregnation is better from the point of view of the vacuum formed as a result of the cooling than a cable which has a perfect impregnation.

When the cable is heated the expanding compound reduces the volume of air films present in the cable—they are probably partly absorbed in the compound—but the pressure will in any case increase. The lead will first expand

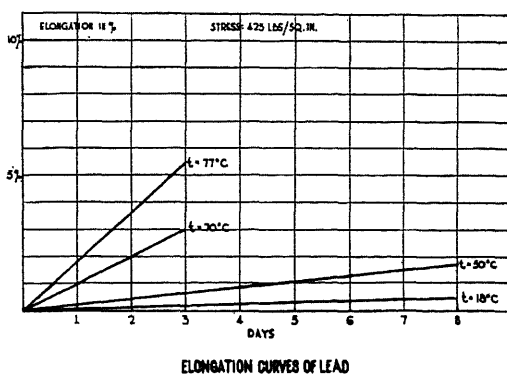


FIG. 65.

elastically under the pressure, but if the stress lasts for a long period the lead will become permanently stretched.

As a matter of fact, lead shows a certain elasticity, but only when the stress is applied for a very short time. If the stress is maintained, the lead commences to elongate permanently, even when the stresses are exceedingly low.

In Fig. 65 some values of the elongation as a function of the time for different temperatures are given. The value of the stresses in the lead sheaths of ordinary high-tension cables may easily reach 600 lbs. per square inch.

Fig. 66 shows the result of a test made on a three-core cable for 30,000 volts working pressure. The two ends of the cable were connected to gauges, care having been taken to remove all gases from the gauges which were filled with oil. The cable, after a period of rest during which formation



of a vacuum was noticed, was heated to  $50^{\circ}\text{C}$ . and then cooled down to  $13^{\circ}\text{C}$ .

It will be noticed that after the cable has reached the maximum pressure it starts showing a decrease, which can be accounted for, at least in part, to the stretching of the lead tube. Many tests have been made in this direction. The pressure inside the cable has been measured, not only by connecting gauges to the two ends, but also by means of gauges connected to different points of a length of cable and also communicating with different parts of a cable section.

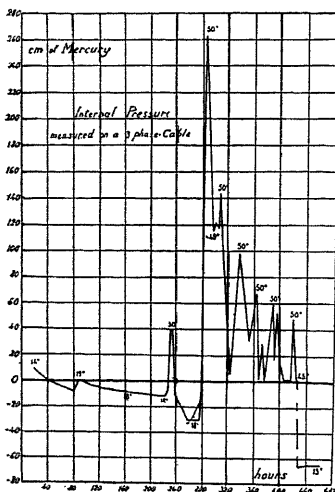


FIG. 66.

The vacuum formed in the cable, due to the drop of temperature following the removal of load, is generally higher than that measured before the application of load; this also seems to be a proof of the increase in the lead sheath.

A probable deformation or collapse of the lead sheath must also be considered when there is a vacuum in the cable, because in many cases the vacuum diminishes with the passing of time.

The presence of gases, however, in the dielectric leads to results similar in some respects to those caused by the deformation of the lead sheath. As a matter of fact, when the gas films are compressed by the expanding compound, they tend to dissolve in this compound, and the pressure in the dielectric is consequently reduced. When the compound contracts, on the contrary, the pressure in the gas films is reduced and some gas is set free; the consequence is a reduction of the vacuum. It is very difficult to say how quickly this phenomenon follows the variation of the pressure, and it is not possible to make any calculation. It is possible that when the dielectric is under tension and ionisation occurs in the gas films, the equilibrium of the free gas with respect to that in solution is reached in a shorter time than when the

cable is not working. There is a certain amount of evidence which leads us to believe that this is probable.

From what has already been said, we arrive at the following conclusion: that the dielectric of a cable contains bubbles or films of gas, the pressure of which can be anything from a vacuum of, say, 27 in. of mercury to a pressure of 80 lbs. per square inch. These figures approximate those actually measured on cables. There is, however, no reason to doubt that these figures may be exceeded in cables impregnated more perfectly or having a thicker lead sheath than those upon which the above tests were made.

Very little can be said with reference to the distribution of these films in the dielectric. The distribution, which results after the impregnation and which is chiefly due to the effect of the absorption by the paper, very probably alters after the cable has been in operation for a little time.

There are probably two factors, besides the action of the paper, which control the distribution of gas films and bubbles in the dielectric; these are the vapour tension of the compound which depends upon the temperature, and the speed with which the gases enter or leave the solution in compound. This factor also depends upon the temperature being mainly controlled by the viscosity of the compound.

It should also be noted that the temperature of cables varies from point to point, the copper being the hottest part and the lead the coolest, and this makes the phenomena still more complicated.

Besides the above-mentioned phenomena, there is the drainage of the compound through the insulation, either through the paper itself or along the surfaces which exist between the paper sheets. This drainage is, of course, greater the higher the temperature at which the cable is working, due to the fact that the cable compound has a lower viscosity at a higher temperature.

Where cables are laid on a slope gravity has the effect of making the compound migrate to the lowest part of the cable. This drainage is, however, reduced in the cables of modern construction, because the porosity of the paper is very low and the tapes are well pressed over each other in such a way as to build up a very compact insulation. There are, however, still two paths open for the migration of com-

pound, one being constituted by the spaces in the copper strand and the other by the gap between the lead tube and the insulation. This gap, which is usually very small in cables which have never been in operation, becomes larger after being worked, due to the expansion of the lead sheath. From tests made in America it has been proved that the passage of the compound along the cable becomes easier after the cable has been in operation. This is probably due to the increase in diameter of the lead sheath. In three-phase cables, either of the belted or screened types, there are also the spaces between the cores which cannot be perfectly filled by the packings.

*The Electric Behaviour of the Gas Films.*

What happens to these gas films when the cable is in operation? Let us first consider the case of a condenser having a dielectric containing gas bubbles. Let us suppose that the condenser is composed of two sheets of impregnated paper separated by a film of air. Suppose that the total thickness of the impregnated paper be  $s$  and that of the gas film  $\sigma$ . The condenser can be imagined as being composed of two condensers in series, one made of impregnated paper and the other of air, the dielectric constants being respectively  $\epsilon$  and one.

If we call  $V_1$  and  $V_2$  the difference of potential acting on the two condensers we immediately have

$$V_1 \frac{\epsilon}{s} = V_2 \frac{1}{\sigma}$$

As  $\frac{V_1}{s}$  and  $\frac{V_2}{\sigma}$  are the gradients of potential in the two dielectrics, we may say that the gradient in the air film is  $\epsilon$  times as great as that in the impregnated paper.

If the thickness  $\sigma$  is sufficiently small (as occurs in a cable) we may consider that  $V_1$  is approximately equal to the voltage  $V$  applied to the condenser. A film of gas in a cable is therefore stressed to a much greater extent than any other part of the dielectric. As the dielectric constant of impregnated paper is about 3.5, the stress across a gas film will be 3.5 times as great as that across the paper.

The consequence of these stresses is that the dielectric

becomes ionised. Mackay and Shanklin have explained what occurs in the following way. The conductor, composed of a dielectric in series with gas in a state of conduction, may be compared to a circuit composed of a discharge tube in series with a resistance or similar current-limiting device. The total characteristic of this circuit (see Fig. 67) is :

$$E = V + Ri$$

$V$  is the voltage across the tube and is given by its integral characteristic. This also is represented in Fig. 67. The first part  $OB$ , for low values of  $V$ , corresponds to a very small

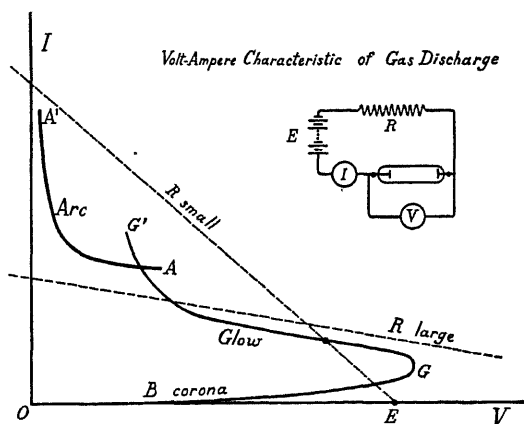


FIG. 67.

current, that is, current carried by the very few ions present in the gas. If  $V$  increases, ionisation by collision starts, and the current increases at this point very rapidly. Ionisation and recombination occur so plentifully that radiation may be visible as in the corona discharge ( $BGG'$ ). The space is now in a comparatively high conductive state and, according to the geometry of the enclosure and the nature and pressure of the gas, the whole system becomes unstable and breaks down into an arc-like discharge ( $AA'$ ). The abscissæ and ordinates in the figure have to be imagined as logarithmic, as the current of the flow and the arc discharge are enormously greater than those of the first period.

$V$  can also be represented in the figure, as its value is

$$V = E - Ri$$

It may be represented by a straight line which makes, with the axis of the abscissæ, an angle :

$$\tan \alpha = R.$$

By changing the voltage  $E$  and leaving  $R$  constant, the line is moved parallel to itself. The different values of  $i$  and  $V$  corresponding to the different voltages are given by the intersection of the straight line with the curve representing the internal characteristic of the tube.

It is easy to see that if  $R$  is small the entire glow discharge may be skipped over. If  $R$  is large, on the contrary, the glow discharge is possible over the entire range by changing the voltage  $E$  applied to the circuit.

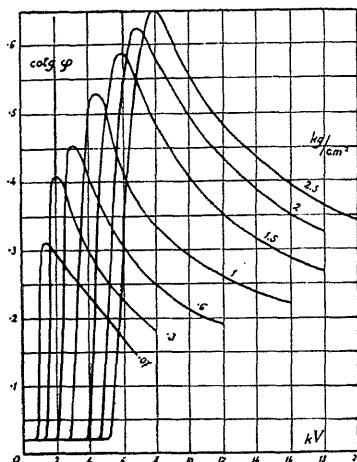


FIG. 68.

A dielectric containing gas films may be considered as a circuit composed of a discharge (the gaseous film) in series with a high resistance formed by the solid dielectric. (This acts, as a matter of fact, not as a resistance, but as a capacity in series.)

When the voltage applied to the dielectric containing a gas-pocket increases, the value of  $\cot \varphi$  remains a constant

until the tension produces a gradient in the gas-pocket sufficient to start ionisation by collision. At this voltage the power factor starts to increase and continues to do so with the growth of the voltage until the internal characteristic is positive. When the glow discharge stage is reached a slight increase of current is accompanied by a large drop in the voltage of the gas film. The energy dissipated in the gas film decreases accordingly, because it becomes a relatively good conductor. The damage to the insulation, on the other hand, may be great, and eventually a spark or distinctive arc-like discharge may occur.

Fig. 68 shows the value of  $\cot \varphi$  measured on a condenser made of glass plates separated by a small air gap. The different curves represent the variation of  $\cot \varphi$  with the

increase of voltage for different pressures in the gas films;  $\cot \varphi$  is a constant and corresponds to that of the mixture—air and glass—which forms the dielectric of the condenser. until the ionisation voltage in the air is reached. At voltages greater than those mentioned the value of  $\cot \varphi$  increases until the glow discharge is reached in the gas film. For higher voltages it diminishes as already explained. The voltage at which ionisation commences depends, of course, upon the pressure of the gas and decreases as the pressure decreases, as can be seen from Fig. 68. The same type of curves may be obtained on condensers made of impregnated paper, which contain, of course, gaseous pockets or films. Such condensers may be considered as being cable models and are of great help when studying what might happen in actual cables.

The curves which have been shown are very typical and correspond to definite pressures in the dielectric. In a cable, not only the electrical gradient varies from point to point, but also the mechanical pressure is far from being uniform throughout the whole dielectric. The curves which it is possible to obtain on working cables are, therefore, not so well defined as those shown in the figure.

In addition to this the curves in the figure correspond to relatively large thicknesses of gas films, whilst the thickness of air films in cables, except in cables of bad construction, are very small.

From experiments made on cable models having a small thickness of gas a curve similar to that shown in Fig. 69 is usually obtained. This is very like those obtained on a cable. On the same figure the capacity shown by the condenser is also given.

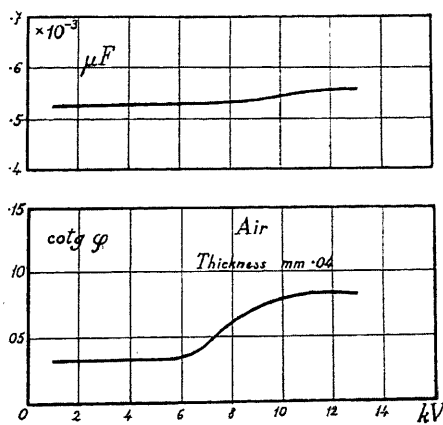


FIG. 69.

It is very interesting to note that there is a value of the thickness of the gas film which does not show ionisation whatever the pressure in it.

The relation between the pressure and the sparking voltage is shown in Fig. 70.

For a given distance between electrodes there is a pressure at which discharge occurs at a minimum sparking potential; this is independent of the gap as is shown in the figure.

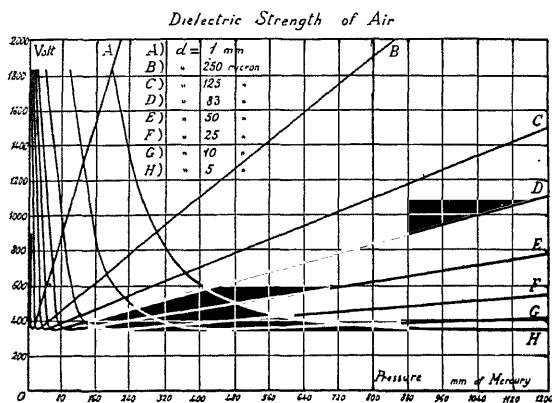


FIG. 70.

The minimum tension varies with the nature of the gas, *i.e.* :

Air	.	.	.	.	241 volts r.m.s.
Nitrogen	.	.	.	.	179    "    "
Hydrogen	.	.	.	.	205    "    "
Oxygen	.	.	.	.	322    "    "
Carbon-dioxide.	.	.	.	.	298    "    "
Acetylene.	.	.	.	.	325    "    "

If an air or gas film in the cable dielectric is so thin that at the maximum potential applied to the cable the voltage across the film is lower than 241 volts, no matter what the pressure is, no ionisation can take place. For instance, if in a single-core cable of 66,000 volts the maximum tension on each core is supposed to be not greater than 80,000 volts, the film of air which does not show ionisation must be smaller than one-hundredth of a millimetre (0.4 mil.). It has been proposed, with the object of increasing the ionisation

voltage, to create a gas in the cable before the impregnation which shows a high minimum rupturing voltage.

Owing to the fact that the conductivity of the ionised gas films is not a constant, a certain deformation of the current flowing through the dielectric is produced. Fig. 71 shows the curve of the current through a condenser containing gaseous films. If the voltage is increased over a certain value the current curve is distorted, the distortion being greater the higher the voltage.

The distorted sine wave may be considered as a pure sine wave accompanied by harmonics. The harmonics commence at the voltage at which ionisation starts, and a method has therefore been suggested of determining the ionisation voltage by determining the voltage at which harmonics commence. This method is realised by a Wheatstone bridge which can be thrown out of balance when the frequency of the current passing through it differs from that of the fundamental sine wave. This method is very sensitive.

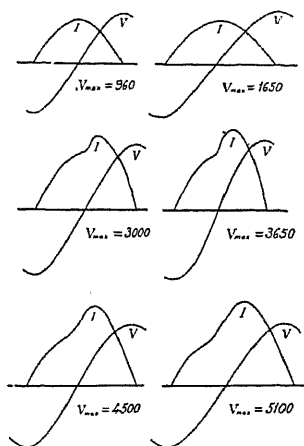
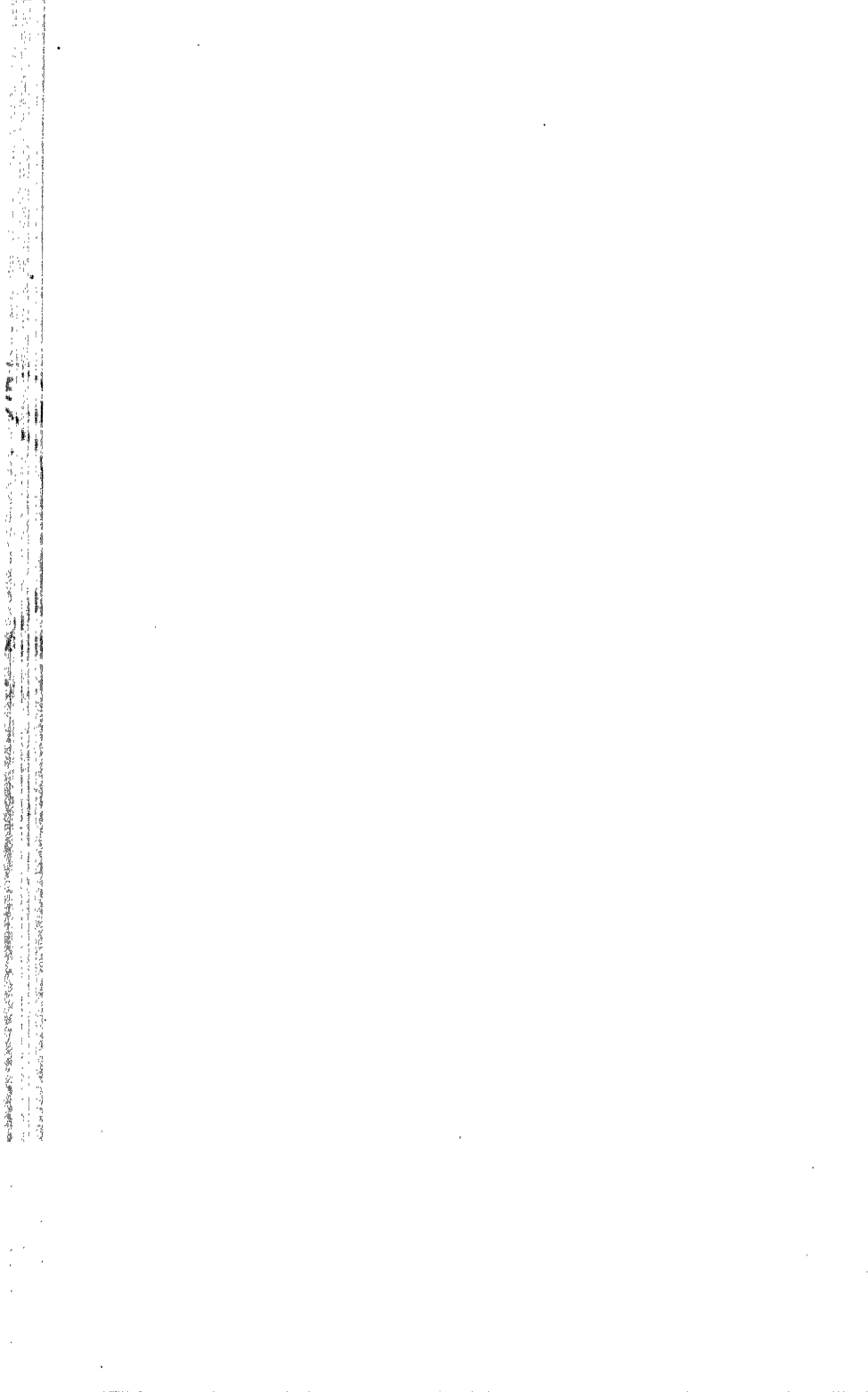
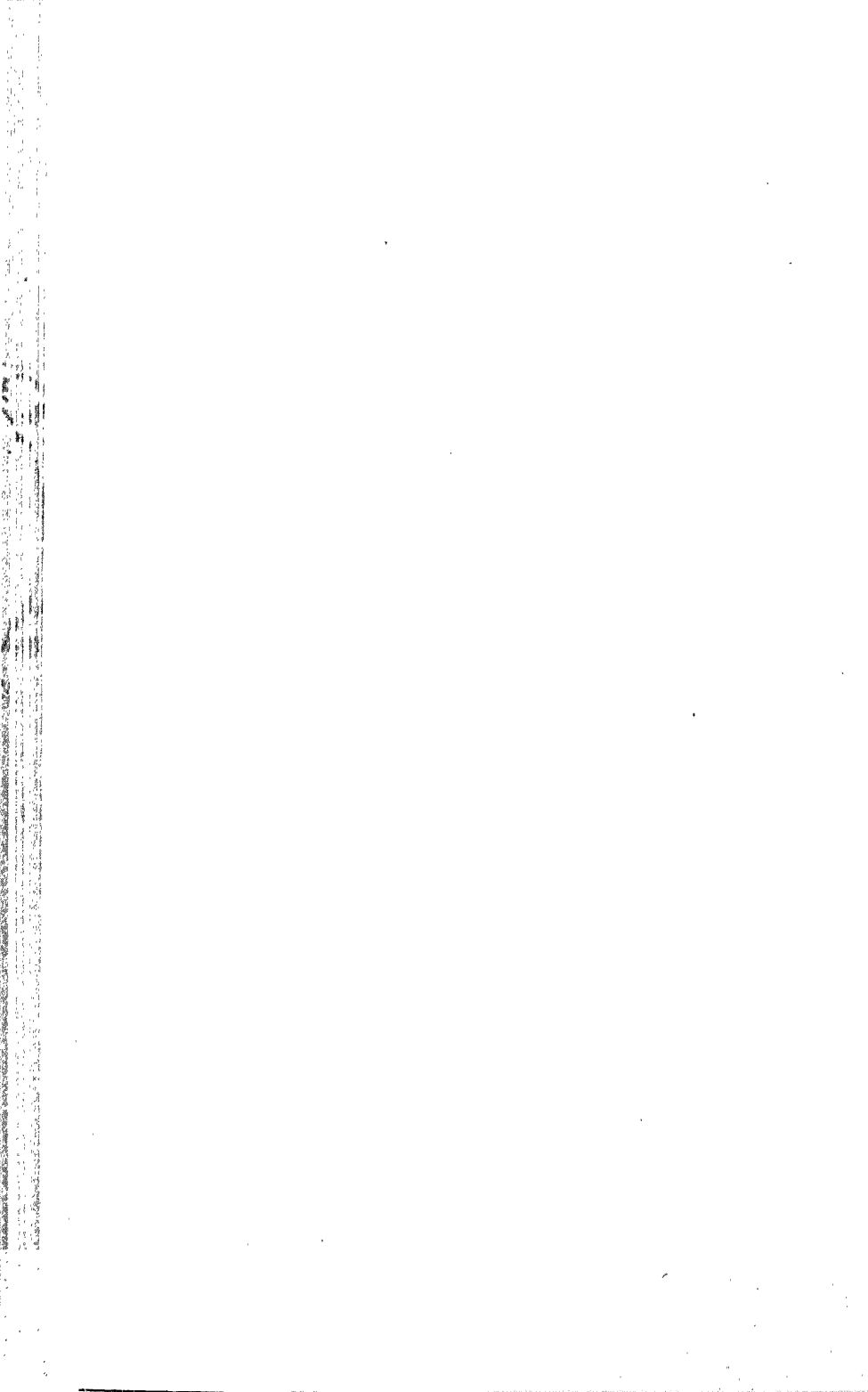


FIG. 71.





## LECTURE V



## LECTURE V

### MECHANICAL AND ELECTRICAL PROPERTIES OF THE FINISHED CABLE

#### *The Behaviour of the Cable when bent.*

WITH regard to the mechanical properties of the cable, the pressures to which the dielectric is subjected have been discussed in considerable detail. It will, however, be of interest to say a few words about what occurs in the dielectric of a cable when it is bent.

Let us first suppose that, in a single-core cable, the impregnated paper forms around the conductor a tube which is made of layers of paper laid continuously along the entire length of the cable. If the cable is bent to a radius  $\rho$ , the fibres of paper which lie on the outside of the curve will be stretched, and those inside will be compressed. If a length of cable corresponding to an angle  $\alpha$  is considered, the length measured along the axis of the cable will be

$$\rho\alpha$$

and the length of the outside surface will be

$$(\rho + r)\alpha$$

where  $r$  is the radius of the cable. The elongation which the paper has to withstand on a length  $\rho\alpha$  is  $ra$ . The percentage of elongation will be

$$\frac{r}{\rho}100.$$

As has been said, the paper is laid on the conductor in such a manner that it is stressed transversely when the cable is bent. Two per cent. was given as an average value of the elongation before breakdown of the impregnated paper, but if the value of  $\frac{1}{2}$  per cent. is considered as safe, we arrive at the conclusion that a single-core cable should not be bent to a radius greater than that given by

$$\frac{r}{\rho}100 = 0.5,$$

*i.e.,*

$$\rho = 200r$$

We can therefore say that the radius of curvature should not be smaller than 100 times the diameter of the cable under the lead. This consideration leads to a very large value for the radius of curvature allowable in a cable, but it is based on the assumption that the paper is laid on the conductor in the form of a continuous tube. This may be true for a very tight insulation. In ordinary cables, however, the paper is laid helically on the conductors in the form of tapes. If these tapes are sufficiently narrow and if the friction between the layers is also slight, the tapes slip one over the other, and the paper is consequently not subjected to any stress. This is what actually happens in a cable in which the insulation is not applied too tightly.

The drying process assists a great deal in this last respect,

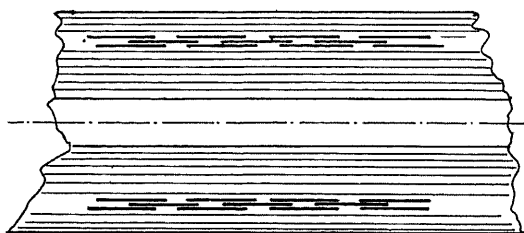


FIG. 72.

because the paper fibres contract during the drying, and, in consequence, the volume occupied by the paper is reduced, leaving a small gap between the layers. The mineral oil used in the impregnation acts as a lubricant, and causes the paper layers to slip more easily.

Suppose we bend a cable with different radii of curvature. There is a radius sufficiently small to cause the paper of the dielectric to be stressed.

Fig. 72 represents in section and in a schematical form some of the layers of a cable when straight. The same thing is shown in Fig. 73, but with the cable bent to such an extent that the paper tapes assume a position in which they commence to react against the bending.

It is a very difficult matter to make a complete mathematical theory which will take into account the fact that the tapes are helically wound, that the paper can withstand a certain amount of deformation, etc., but it is easy to see

that the minimum radius of curvature, corresponding to the locking of the tapes in the cable, is smaller the narrower the tapes, and the greater the gaps left between them, *i.e.*, the softer the insulation laid on the conductor. It is also evident that when the temperature is very low and the compound stiff, the bending becomes dangerous, as it is difficult for the layers of paper to slip between each other. In many cases it is necessary to heat the cable before being able to commence laying. In cables in which the usual compound has been used, it is necessary to use some precaution when a temperature of zero degrees Centigrade is reached.

Although it would be better to make the insulation very

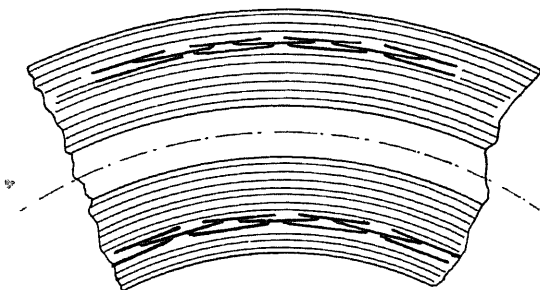


FIG. 73.

soft to facilitate the bending of the cable, the tendency during these last few years has been in just the opposite direction, that is, to make the insulation rather tight. The reason for this is that a tight insulation is much better from an electrical point of view. The only other thing which it is possible to do is to decrease the width of the paper tapes. The extent to which this can be done, however, is limited, so that it is advisable to bend the cable as little as possible and to despatch it from the factory on large drums.

In a three-phase cable, besides the belt, which behaves more or less in the same way as in a single-core cable, with the only disadvantage that the diameter of the cable, and therefore the movement of the tapes, are greater, there are the cores to be considered. The insulation of these also behaves in a manner similar to that found in a single-core cable, but it must be noted that they are already bent even when the

cable is straight. In this case the radius of the curvature of the cores is that of the helix they form. When the cable is bent with a radius of curvature  $\rho_1$  the minimum resulting radius of curvature of the cores is

$$\rho = \frac{1}{\frac{1}{\rho_1} + \frac{1}{\rho_2}}$$

where  $\rho_2$  is the radius of curvature of the helix formed by the

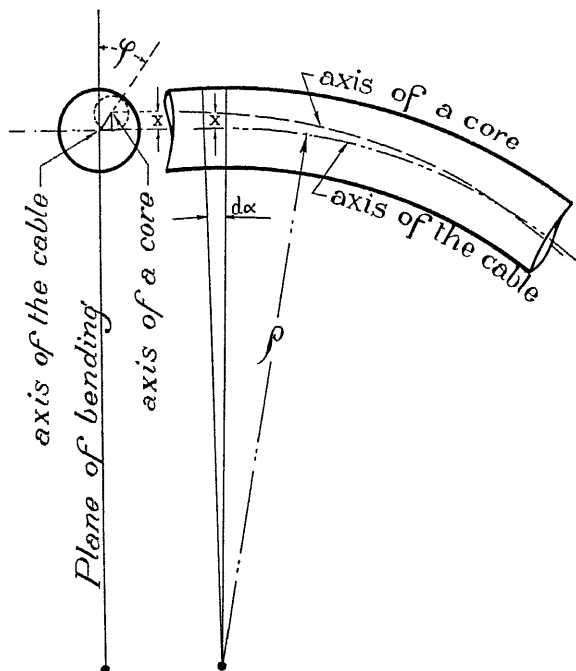


FIG. 74.

cores. It is generally the belt which limits the curvature to which the cable can be bent.

There is also the movement, which is always considerable, of each core with respect to the other, which has to be considered.

To calculate this movement, let us consider a three-core cable bent according to a radius  $\rho$  as represented in Fig. 74. The length of the axis is supposed to be the same as before

bending. Let us consider a length corresponding to an angle  $d\alpha$ ; this length will be  $\rho d\alpha$ . It is quite clear that a length of core at a distance  $x$ , and corresponding to the length  $\rho dx$  of the axis, must be longer after the bending than before, or, if this increase of the length is not possible, one of its ends will have moved an amount equal to the increase of length which would have occurred had it not been for the inelastic nature of the core. This is evidently equal to :

$$x d\alpha$$

The distance  $x$  from the axis changes from point to point as the core is helically wound, but it can be calculated as follows. (See in Fig. 74 the part which represents the section of the cable.) If  $\varphi$  is the angle made with the plane of bending by the line connecting the axis of the cable with that of the core at the point we have under consideration, and  $r$  is the distance of the two axes

$$x = r \cos \varphi$$

Now if we consider a certain length of cable which corresponds to an angle  $\rho\alpha$  measured from the point where  $\varphi$  is zero, it is clear that the angle  $\varphi$  corresponds to the length  $\rho\alpha$  as the angle  $2\pi$  corresponds to a length equal to the lay of cabling of the cores. That is to say :

$$\frac{\varphi}{\rho\alpha} = \frac{2\pi}{t}$$

from which :

$$\varphi = \frac{2\pi\rho}{t}\alpha$$

If we substitute this expression in the formula given above for the elementary movement of the core, we obtain :

$$d\lambda = r v s \frac{2\pi\rho}{t} d\alpha$$

the total movement on a length of cable corresponding to an angle  $\alpha$  will be the integral of  $d\lambda$  extended between the limits zero and  $\alpha$ , i.e.,

$$\lambda = \left[ \frac{rt}{2\pi\rho} \sin \frac{2\pi\rho}{t} \alpha \right]_0^\alpha$$

The maximum movement is obtained when  $\alpha$  is comprised between two values such that :

$$\sin \frac{2\pi\rho}{t} \alpha$$



varies from 1 to  $-1$ . In this case the integral becomes equal to

$$\frac{rt}{\pi\rho}$$

This is the movement of one core with respect to the axis of the cable. The movement with respect to the other cores may be greater than this, and it can be demonstrated that it may be as great as

$$\frac{3rt}{2\pi\rho}$$

This occurs when the angle is  $\pi$ , and equal to 180 degrees, *i.e.*, for a bend corresponding to a semi circle.

Imagine a 33,000 volt three-phase cable having the following values :—

$$\begin{aligned} r &= 3.7 \text{ cm.} \\ t &= 140.0 \text{ cm.} \end{aligned}$$

If the cable is bent according to a radius  $\rho$  of 70 cm. and at an angle  $\alpha$  of 180 degrees, the movement of a core with respect to the others may reach the value of about 3.6 cm.

It can therefore be seen that these movements of the cores are large. In a screened type of cable there may be only the danger of spoiling the metallised paper or of upsetting the position of the metal tape, but in the belted type the likely dangers are much greater.

If a cable is bent so that its radius of curvature is small when compared with its total length, it is very difficult for the cores to move in the way which has been studied above, because it is impossible for them to elongate or contract elastically.

This latter movement of the cores, which is radial instead of being in the direction of the axis, leads to a separation of the cores and to the formation of empty spaces between them and the fillers. It also places a great strain upon the belt.

### ELECTRICAL PROPERTIES OF THE CABLE

#### *General Information.*

Referring now to the electrical properties of high-tension electric cables, there is very little to add to what has already been said on impregnated paper. One of the fundamental electrical characteristics of a cable is its insulation resistance ;

this can easily be calculated if we know the resistivity of the impregnated paper of which the dielectric is composed. It should be pointed out that one generally obtains, when testing the finished cable, values which are much higher than those calculated. This is largely due to the fact that the gas films present in the insulation reduce the path through which the current flows. A similar increase in the actual value obtained with respect to that calculated has also been noticed in the thermal resistance, and is due to the same cause. In well-made cables, however, these differences are very small.

There is also very little more to be said about the capacity, it having already been fully discussed in Lecture III.

The insulation resistance loses all its significance in high-tension cables, but, on the other hand, the dielectric losses are of great importance.

#### *Dielectric Losses.*

Dielectric losses are important, firstly, because they constitute a source of dissipation of power which, increasing with the tension, is of no importance in low-tension cables, but needs greater consideration the higher the working voltage. The following figures give an idea of the amount of these losses as compared with the total losses permissible in the cable, the total losses being the sum of the Joule losses in the conductor and the dielectric losses :—

	Total losses.	Dielectric losses.
Three-phase cable, belted type, 25,000 volts, 0.15 sq. in. . . . .	40	0.65
“T.L.S.”, 33,000 volts, 0.15 sq. in. . .	50	3.0
Single-core, 66,000 volts, 0.15 sq. in. .	50	6.0
Single-core, 132,000 volts, 0.15 sq. in.	50	26.0

It is evident that in high-tension cables the carrying capacity is reduced to a great extent by the presence of the dielectric losses and that their reduction is highly desirable.

When a cable is tested for dielectric losses it can be imagined as being a condenser having two plates—a single-

core cable corresponds exactly to this assumption. If the cable is of the "T.L.S." or screened type, each one of the cores, together with the lead, can be considered and tested as a single-core cable. If the cable is of the three-core type, it is general to connect two of the cores to the lead and to make the tests, considering the remaining conductor as one of the plates, and the lead with the other two conductors as the second plate.

It is quite clear from what has been said in the previous lecture, that at very low testing voltages the  $\cot \varphi$  measured is not affected by the presence of gas films, but that these should come into play when the testing voltage is increased over a certain value, which is called the ionisation voltage.

It is laid down in cable specifications in the United States and Italy—the information probably coming from the same source—that  $\cot \varphi$  has to be measured at a tension corresponding to 20 volts for each mil of thickness of the dielectric of the cable, and also at 100 volts per mil. The difference in power factor is considered as a measure of the ionisation, and should not exceed the value of 0.02 in a three-phase cable and 0.01 in single-core cables. These values are now a little too high, however, as they conform to experiments made about four years ago. The temperature at which the test should be made is that of the surroundings.

It has been suggested that it would be convenient to state in cable specifications the maximum difference in the power factor expressed as a percentage of its value. From what has already been said, it is quite clear that there is no connection between the power factor shown by the cable at a low voltage (this is entirely governed by the quality of the compound, its temperature and the frequency of the current used), and the power factor measured at higher voltages, which depends upon the ionisation of the gases entrapped in the dielectric. This also depends upon the temperature of the cable and upon the frequency of the current used to make the test, but according to laws which are entirely different from those of the compound.

It is therefore wiser to consider this increase of the power factor separately and independently from the power factor shown at low voltages.

Methods for making three-phase measurements of power

factor in three-core cables have been suggested, but, besides being very cumbersome, they are practically useless. As a matter of fact, the power factor of the dielectric is independent of the shape of the condenser on which it is measured, and consequently should be equal when measured single-phase or three-phase. The presence of the gas films, however, changes the situation at tensions higher than that of the ionisation, and there is actually a difference between the power factor measured in three-phase, and that measured in single-phase. This difference refers, however, only to that part of the power factor which is of importance in ascertaining if the cable has been well impregnated.

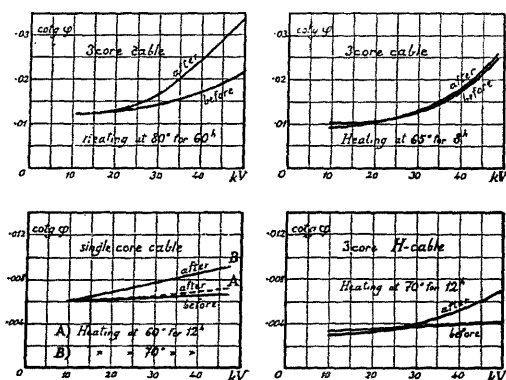


FIG. 75.

Three-phase cables of the belted type give the worst results. The values of  $\cot \varphi$  given in Fig. 75 refer to three-phase cables for 33,000 volts.  $\cot \varphi$  has increased with the increase of tension, which indicates the ionisation of the gas films entrapped in the insulation. The tension at which the ionisation commences is not well-defined, owing to the fact that the dimensions of the gas films, their position in the electrostatic field, and the pressure are all variable elements. The last-mentioned point—the pressure—is that which has the greatest influence.

Before discussing the effect of the load, let us first consider single-core cables. In these cables the ionisation losses are much smaller, this being due to various reasons. Firstly, it is much easier to build up a very compact dielectric in a

single-core than in a three-core cable, and also the total volume of compound present in a single-core cable is considerably smaller, so that the amount of contraction due to cooling is also smaller. Then, again, tangential stresses are totally absent.

After load, the deviation from constancy of  $\cot \varphi$  may increase if the load has been great enough. This is due in part to the change in the distribution of the gaseous films, and partly to the stretching of the lead sheath. The results

of some tests are shown in Fig. 75, and require some comments.

In the first diagram there is a big variation of the power factor before and after the heating. In the second the variation is very little. This is due to the fact that in the second curve the temperature to which the cable was heated is smaller and also to the fact that the change of power factor with the voltage was also rather large before the heating, which signifies that the volume of gas present in the dielectric was considerable.

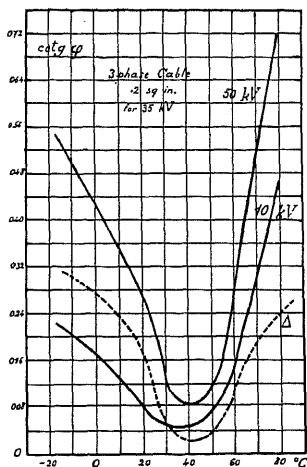


FIG. 76.

This gas during heating has acted probably as a cushion, reducing the pressure in the dielectric due to the expansion of the compound and consequently reducing the stretching of the lead.

The single-core cables show a smaller alteration after heating, probably because the volume of compound in the single-core cable is much smaller than that in the three-core type, and again, the gaseous spaces are more distributed in the dielectric than in the case of a three-core cable, where they are apt to occur mostly between the cores and fillers.

We have considered, in all that has hitherto been said, the deviation from constancy of  $\cot \varphi$  as a measure of the ionisation. This method is, as a matter of fact, the only one which has been used for some years, but has, of course,

its own disadvantages. It gives only an average value of the ionisation in the cable, and does not show at all if this is concentrated at definite points or in which part of the cable, and the results obtained on any one cable are often not as consistent as would be desired, this being no doubt due to the irregular distribution of the gas films.

This method, however, seems to be the only one available up to the present time.

The ionisation measured on a cable is, of course, influenced by the temperature, as is shown for a three-phase cable in Fig. 76, which shows the values of  $\cot \varphi$  measured on a three-phase cable at 10 kv., and at 50 kv. as a function of the temperature of the cable. The difference of the values measured at the two tensions is also plotted (Curve  $\Delta$ ).

At low temperatures the ionisation is very high, due to the fact that the compound has contracted, and that the total volume of the air films is at its maximum value and their pressure very low. The volume diminishes at higher temperatures, with a resulting increase in pressure, and relative decrease in the ionisation, until very low values are reached. This is probably due to the very high pressure of the gas and also to the fact that a large part of the gas dissolves in the compound.

The further increase in the ionisation is probably not due to the gas, but to an increase in the power factor in the compound itself. We have already seen that this may occur if the temperature and the electrical gradient are sufficiently high.

Single-core cables behave in a very similar way, showing, of course, a much smaller value of ionisation.

### *Breakdown Voltage.*

The breakdown voltage of a cable is influenced by the nature of the current, and by the time for which the voltage is applied.

The first two points have been already discussed in Lecture II., but it will be useful to give some additional information regarding the influence of the time of application.

Fig. 77 shows the life curve of a three-phase 25,000-volt cable; the values of the breakdown voltages are plotted as ordinates, and the time taken to reach the breakdown as

abscissæ. It will be noticed that the decrease of the break-down voltage with the increase of time is very remarkable; thus for a short time, say for about one minute, the break-

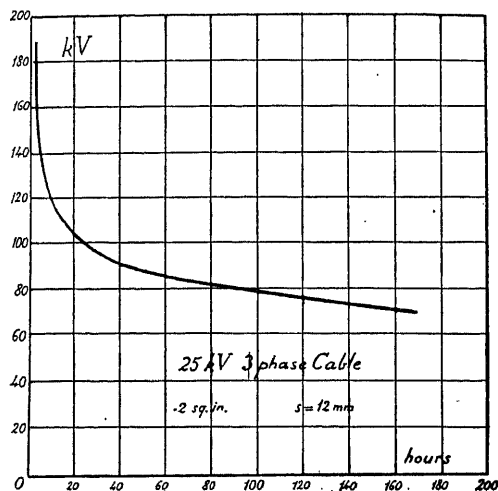


FIG. 77.

down pressure is about 200,000 volts, the corresponding pressure after 100 hours is only 80,000 volts.

If the applied tension is removed for a time, the life of the sample does not appear to be affected by this period of rest. Also the power factor taken on a sample shows an increase, which is not affected by an eventual period of rest.

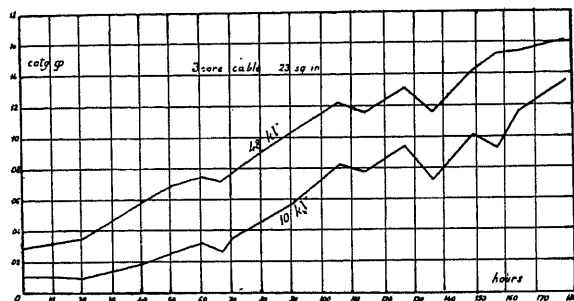


FIG. 78.

Fig. 78 shows this increase in the value of  $\cot \phi$  measured at 48 and at 10 kv., the test being made on the same cable as that of the life curve. After a time the values

become so large that one must expect a great alteration in the properties of the dielectric. A similar alteration has been found on cables after a long period of service, and has been attributed to the formation of water in the dielectric, as will be described later.

Fig. 79 shows the life curve of a single-core cable. In this type of cable the drop of the breakdown voltage with the increase of time is not so marked as in a three-phase cable. It is therefore evident that the causes of breakdown which are present to a large extent in the three-phase cable, are

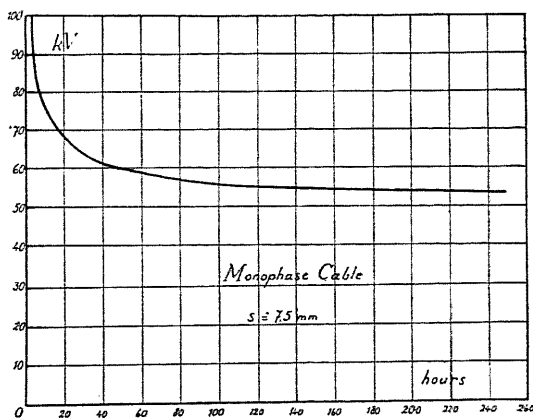


FIG. 79.

greatly reduced in a single-core cable. Also the increase in the power factor, so evident in the three-phase cable, is less noticeable in the single-core cable.

#### THEORIES FOR THE BREAKDOWN AND CABLE DETERIORATION.

Among the different theories for the breakdown of solid dielectrics which have been proposed during the last few years, two especially are worthy of mention. The first is the Wagner theory, which can be briefly described as follows:—

Consider a dielectric which is not perfectly homogeneous so that the current flowing through has a tendency to concentrate on certain lines of flow. Let us consider one of them. The amount of power which is dissipated in it is proportional to the voltage applied to the dielectric and to the current passing through this channel. Let us suppose the voltage to be constant but the temperature of the dielectric changed.



As the resistivity diminishes with the increase of temperature the power dissipated also increases, as is represented in Fig. 80 by the curve  $V_1$ . The amount of power which can be dissipated from the conducting canal through the dielectric can be represented by a straight line  $t_0A$ ,  $t_0$  being the temperature of the dielectric. It is evident that the temperature and the power dissipated in the channel we are considering are determined by the point  $a$  at which the two lines cross.

If the tension applied to the condenser is increased, the energy dissipated also increases, and the curve representing

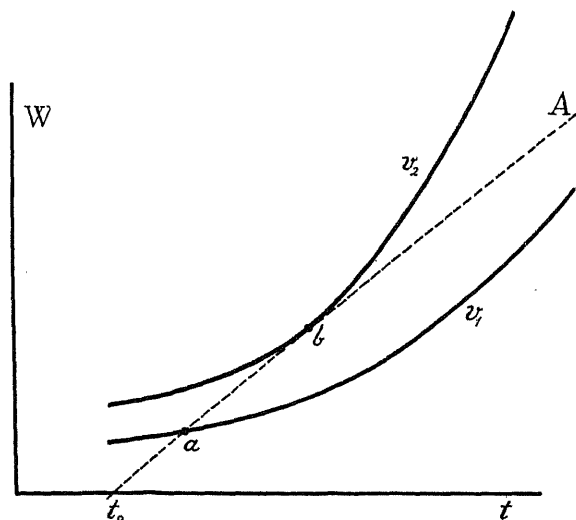


FIG. 80.

it is therefore higher than  $V_1$ . Let us suppose it to be represented by the curve  $V_2$  tangent in  $b$  to the line  $t_0A$ . The temperature and power dissipated now correspond to those defined by the point  $b$ , but, as can easily be seen, a condition of instability is reached. As a matter of fact, any slight increase of temperature or of voltage leads to the impossibility of having a point of equilibrium. The temperature may therefore increase continuously up to the destruction of the dielectric, owing to the fact that the dissipation of the heat is not sufficient.

The Wagner theory has been modified and completed by Rogowski Karman Semennoff to include uniform heating of

the whole dielectric, and not merely local heating at accidentally defective spots.

Another theory is based on an assumption very similar to that of the theory of the discharge in the gases. Under the action of the electrostatic field, the ions present in the dielectric move in the direction of the field. The speed of an ion assumes a constant value which is determined by the average friction caused by its movement (collision of molecules and ions). If the electrostatic field is increased, the speed of the ion also increases. These ions, however, can attain such a speed that they acquire sufficient energy to ionise by impact the dielectric. When this occurs, every impact produces new ions which, in their turn, also produce other new ions by impact. In this way the number of free ions becomes very large, and, as a consequence, the current through the dielectric also becomes large. A breakdown is therefore inevitable. According to this theory, the distribution of the dielectric stresses is not so simple as we have supposed in Lecture III., but is complicated by the formation of space charges. Joffé has shown that, according to this theory, very small thickness of dielectric can stand stresses as high as 150 million volts per centimetre, and has actually proved this experimentally.

At high temperatures the electric breakdown appears to be due to heating caused by the current, as is assumed in the first theory. At low temperatures the breakdown seems to occur as explained by the second theory, that of the ionisation by impact.

Cables have a dielectric which is partly solid—the paper—and partly liquid—the compound. According to some authors, the theory of the electric discharge in the liquid dielectric is very similar to that of the gases (ionisation by impact). Another theory claims that the friction caused by rapidly moving ions produces vapours which build up a gaseous track in the oil, through which the discharge assumes the usual form of that through gases.

There is, however, a very important cause of the breakdown which must be considered, that of the presence of gaseous films and pockets in the dielectric; this probably is the only fact which is responsible for the failure of attempts to correlate the results of breakdown tests made on con-

densers composed of paper sheets between flat electrodes, and the gradients corresponding to the breakdown voltage of a cable.

A very interesting study printed, but not published, has been presented by Hirschfield, Meyer and Connell. This study is in two parts, the first being printed in 1927, and the second in 1928. In this article very valuable information is given concerning the pressures and vacuum developed in a cable, and a theory of the mechanism of cable deterioration is also considered. According to the authors, the gas films become ionised when the cable is in service, and this ionisation is especially important when the cable is not loaded, because vacuum develops in it. The result of ionic bombardment on the insulating compound is a polymerisation of the constituents of the compound. This product of polymerisation is well-known and is a kind of wax which does not melt at high temperatures and which is not soluble in ordinary solvents. This wax has been produced in laboratories by exposing mineral oils to an ionic bombardment, obtained either with a Coolidge tube, or with a glow discharge in an evacuated tube, or even with a corona discharge from a copper wire.

An increase in the molecular weight has also been found in insulating compound extracted from used cables, even where the wax was not readily noticeable.

The production of wax is accompanied by the production of gases, hydrogen being the one which is produced in greatest quantities.

The wax is a very good insulator, and cannot be held responsible for cable deterioration. Hydrogen, on the contrary, may react with carbon dioxide and develop water. Water is, in any case, developed by the effect of the ionic bombardment on the paper, and it is this water formed within the dielectric which is in all probability responsible for the increase of the power factor noticed in service and in the life test, and is no doubt one of the chief causes of the cable deterioration and subsequent breakdown.

This theory of the breakdown explains certain types of breakdowns, and seems to give a sufficient explanation of the deterioration which is evident from the increase of  $\cot \phi$  shown by the dielectric. It should, however, not be for-

gotten that other theories based on purely electrical assumption are also sufficient to explain other types of breakdown.

The very low mechanical pressure to which the dielectric is submitted, especially when the load is off, leads to a low dielectric strength, and consequently the possible breakdown. Besides this the gaseous films, especially when the mechanical pressure is low, are highly ionised and build up conductive laminae which produce distortion in the electrostatic field and stresses along the surface of the paper tapes. At high stresses it has also been found that gases may migrate through the paper sheets under the action of the ionic bombardment and build up an ionised path in the direction of the stress.

It is very probable that all these phenomena occur at the same time, and it is very difficult to ascertain to which one of them the breakdown is actually due.

#### SPECIAL DEVICES TO AVOID IONISATION.

From what has already been said, it is evident that the presence of ionised gas is highly undesirable in high-tension cables. Some methods have been suggested to improve cables from this point of view.

One method is based on the fact that if the mechanical pressure on the dielectric is sufficiently high, no ionisation occurs, and it has consequently been proposed to leave channels in the cable which may communicate with the atmosphere at the joints; but a more complete method has been suggested, that of increasing the pressure over that of the atmosphere using pumps or similar means. These methods, however, have been merely suggestions, and have never been developed. A great improvement in the behaviour of some cables has been obtained in America by filling the joints with very fluid mineral oil which can be supplied by reservoirs connected to the joint. The oil, when the cable is cold, is sucked into the cable, in which there is a vacuum, as has already been shown. The impregnation of the cable is consequently much improved. It is interesting to note, however, that the cable does not cease to absorb oil for a very long time. One of the reasons for this is that the oil takes a very long time to reach the points of the cable far

from the joint, but there is yet another reason which does not very greatly favour the system of feeding joints. The cable, when cold, absorbs the oil fed from the reservoir very slowly. This oil impregnates the points near the joint. When the cable is loaded and becomes heated, the compound expands, but only a very small quantity of the oil mixed with the compound can return to the reservoir, this being due to the fact that the cable heats up quickly, and the return passage for the oil to the feeding reservoir is too small. The lead is consequently stretched.

Whilst in ordinary cables, after prolonged heating due to load, a definite increase in the diameter of the lead tube is reached, and no further increase occurs unless the cable is submitted to a higher load, in the cable which is fitted with an oil reservoir, the empty spaces which remain after a heat cycle are filled with new oil, and the stretching of the lead has no limit. This has been experimentally proved and the lead tube has been burst by repeated temperature cycles.

Very thin oil should not be used to feed the joints. This precaution will at least increase the number of cycles which the cable can withstand without expanding the lead sheath too much.

The commercial lines existing to-day at a maximum operating tension of 132,000 volts, have been designed to be perfectly impregnated, and to be always submitted to a pressure not lower than atmospheric. To obtain this result a proper duct has been provided in the cable to allow the free expansion of the compound into special tanks. The cable is connected at its upper end to a reservoir into which the oil which impregnates the cable can freely expand when the cable is loaded. From this same reservoir the oil returns to the cable when the load is removed. To permit the migration of the insulating oil through the cable without producing too large a pressure, due to the friction in the duct, a thin oil is used, and the design of the duct is ample enough for this purpose. Fig. 81 shows the construction of the cable; the central duct is noticeable and also the presence of a double lead sheath, which is necessary, because of the need to armour the cable with copper tape in order to avoid deformation of the lead sheath. The outer lead is

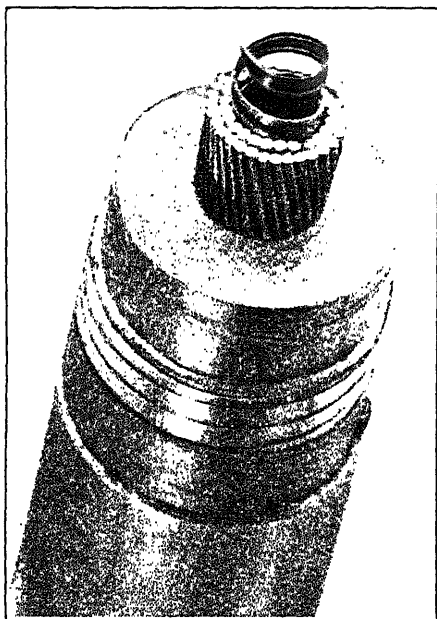


FIG. 81.

*To face p. 106.*



nothing more than a protection to the armouring against the chemical action of the ground.

Two very important lines have been working in the United States for about two years without showing a single electrical fault. One of these two lines, about twelve miles long, is now being duplicated in order to meet the demand for power. A similar line operating at the same tension is working in Italy, and another at 100,000 volts is installed in Germany, all being made on the same principle.

This principle has been extended also to lower tension cables. In Italy a three-phase oil-filled cable has been working for about seven months at 70,000 volts, and in the States another oil-filled cable working at 33,000 volts sector-shaped, has been put into operation near Chicago.

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